Università degli studi di Roma Tor Vergata

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Istituto di Scienze dell'Atmosfera e del Clima

Stratospheric variability and its dynamical impact on the troposphere simulated by chemistry-climate models

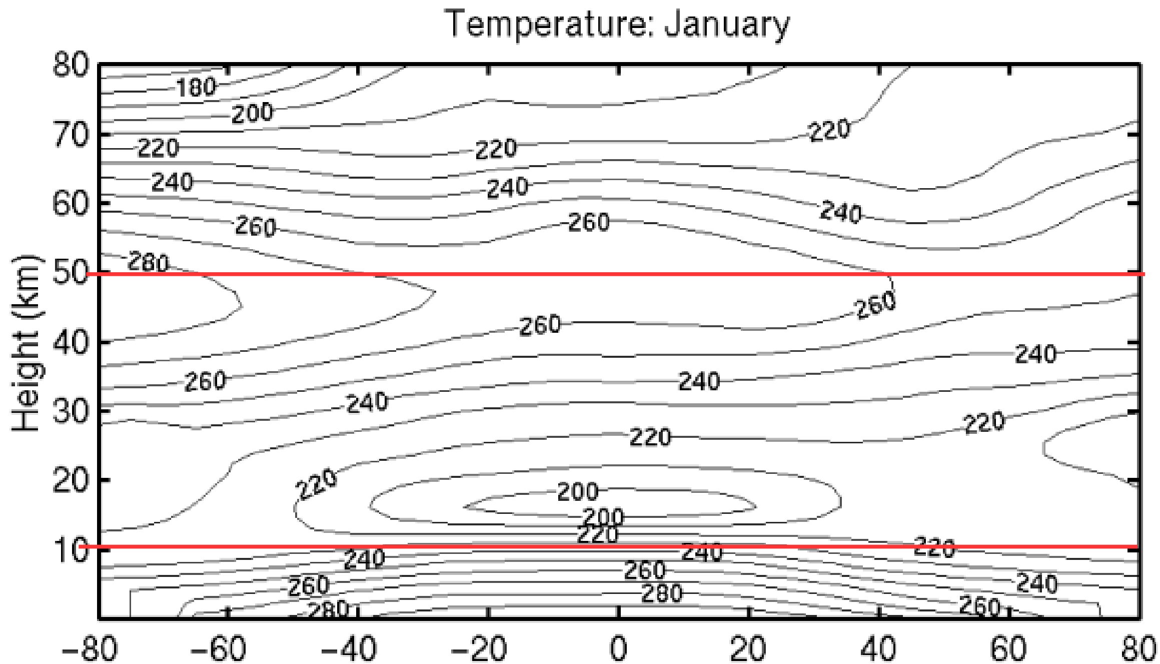
Daniele Minganti

10/02/2017

Mean state of the atmosphere

Thermal wind relationship

$$\frac{\partial u_g}{\partial z} = -\frac{R}{Hf_0}\frac{\partial T}{\partial y}$$

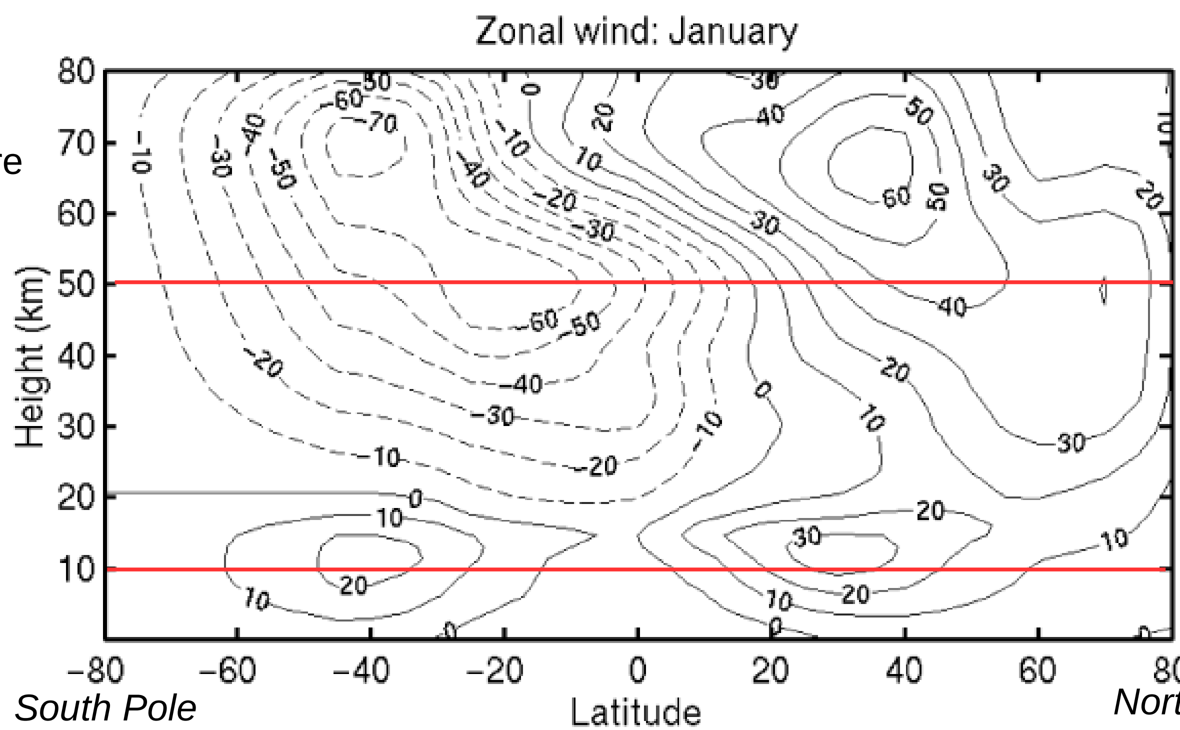


South Pole *North Pole*

Stratosphere

Observed monthly and zonally averaged temperature (***K***) and zonal wind (***m/s***) for the month of January

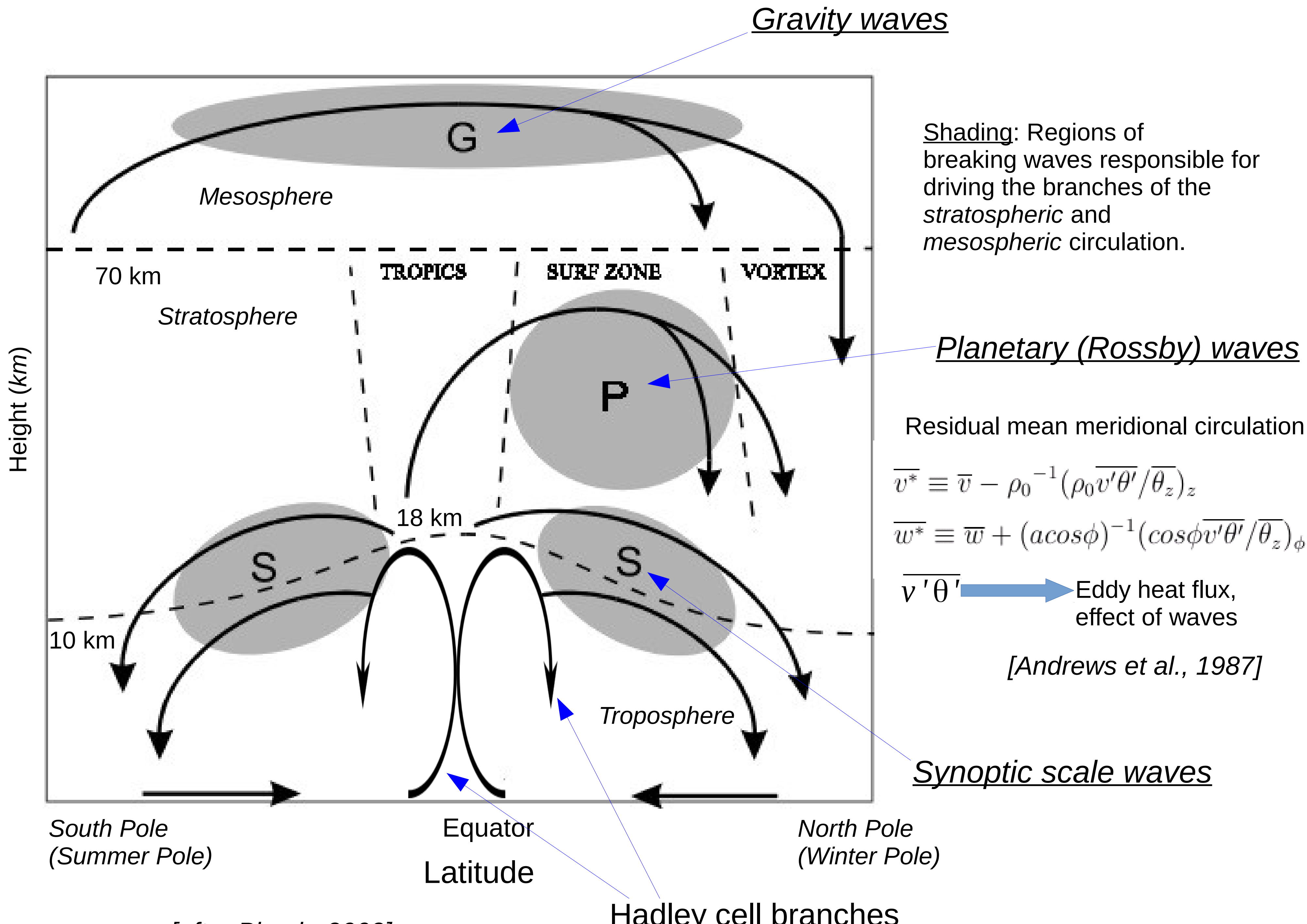
[Holton, 2004]



South Pole *North Pole*

Stratosphere

Wave-driven (B-D) circulation



[after Plumb, 2002]

Shading: Regions of breaking waves responsible for driving the branches of the *stratospheric* and *mesospheric* circulation.

Residual mean meridional circulation:

$$\overline{v^*} \equiv \overline{v} - \rho_0^{-1}(\rho_0 \overline{v'\theta'}/\overline{\theta_z})_z$$

$$\overline{w^*} \equiv \overline{w} + (a\cos\phi)^{-1}(\cos\phi \overline{v'\theta'}/\overline{\theta_z})_\phi$$

$\overline{v'\theta'}$ → Eddy heat flux, effect of waves

[Andrews et al., 1987]

Aim of the work

- Study of the *stratospheric variability*, in particular the wintertime Northern Hemisphere (*NH*) polar stratosphere, and its *effect on the tropospheric circulation*.
- A number of *Chemistry-Climate Model* (*CCM*) simulations is used to evaluate such coupling, together with the "observational" data from *ERA-interim reanalysis*.
- Characterization of *anomalous stratospheric events* and their effects on the tropospheric circulation.
- Implications: evaluation of the *stratosphere as source of predictability* both for climate and weather prediction.

NH dynamics

- ***Sudden Stratospheric Warming* (SSW)**: in the winter season the tropospheric waves can interact with the stratosphere, leading to a *warming of the stratosphere* (up to 40° C) and, in the most severe cases, a *reversal* of the *westerly circulation* is observed. This leads to a *weakening* of the *polar vortex*.

k,l *longitudinal and latitudinal wavenumber*

$$0 < \overline{u} < \beta\left[\left(k^2 + l^2\right) + {f_0}^2 / \left(4N^2H^2\right)\right]^{-1} \equiv U_c,$$

Condition for vertical propagation of stationary (Rossby) waves into the stratosphere

$$f_0 \equiv 2\Omega sin\phi_0$$

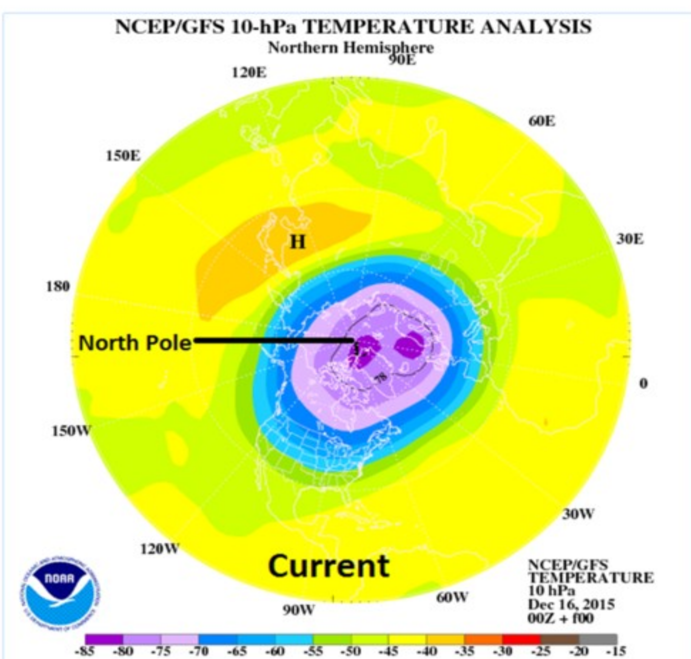
$$\beta \equiv 2\Omega a^{-1} cos\phi_0$$

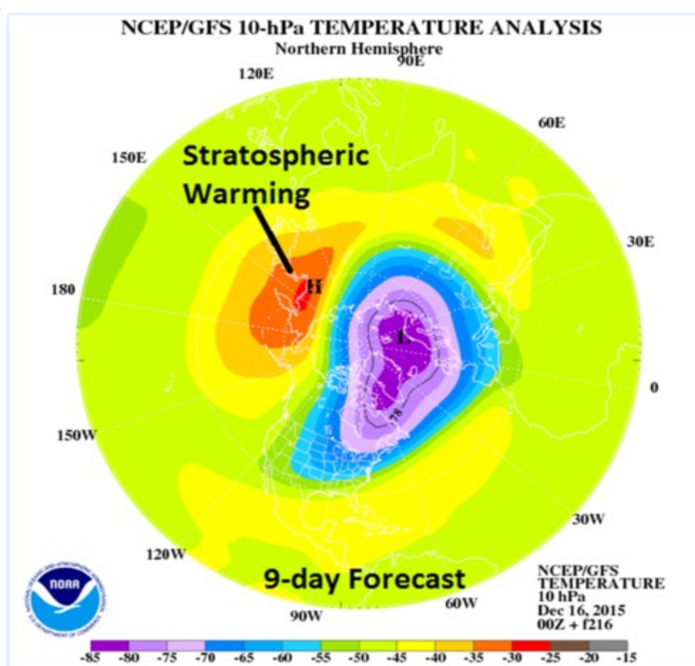
$$N^2 = g\frac{d\ln\theta_0}{dz}$$

Brunt-Vaisala frequency

U_c is the *Rossby critical velocity*

Middle stratosphere

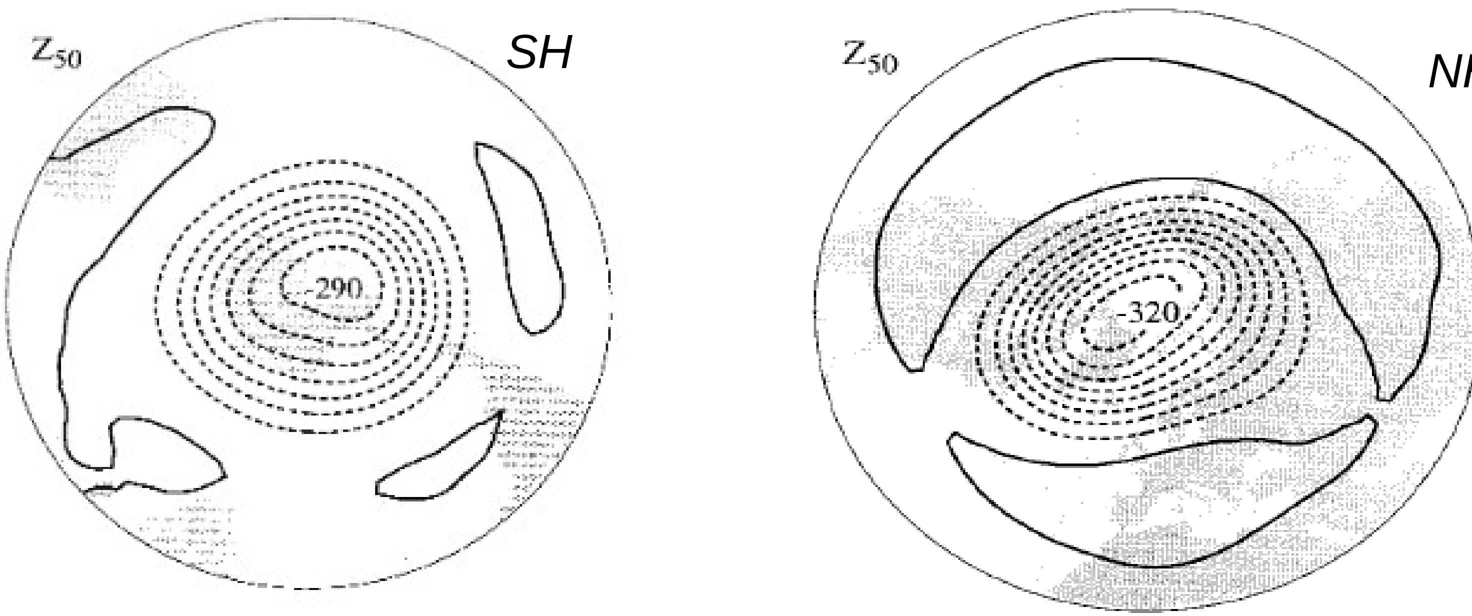




Temperature at 10 hPa

NH dynamics

- ***Annular Modes***: hemispheric variability (pressure, wind), produced by atmospheric mass redistribution, and present at all levels. *Positive phase*: negative pressure anomalies over the Pole, and positive pressure anomalies over the mid-latitudes.

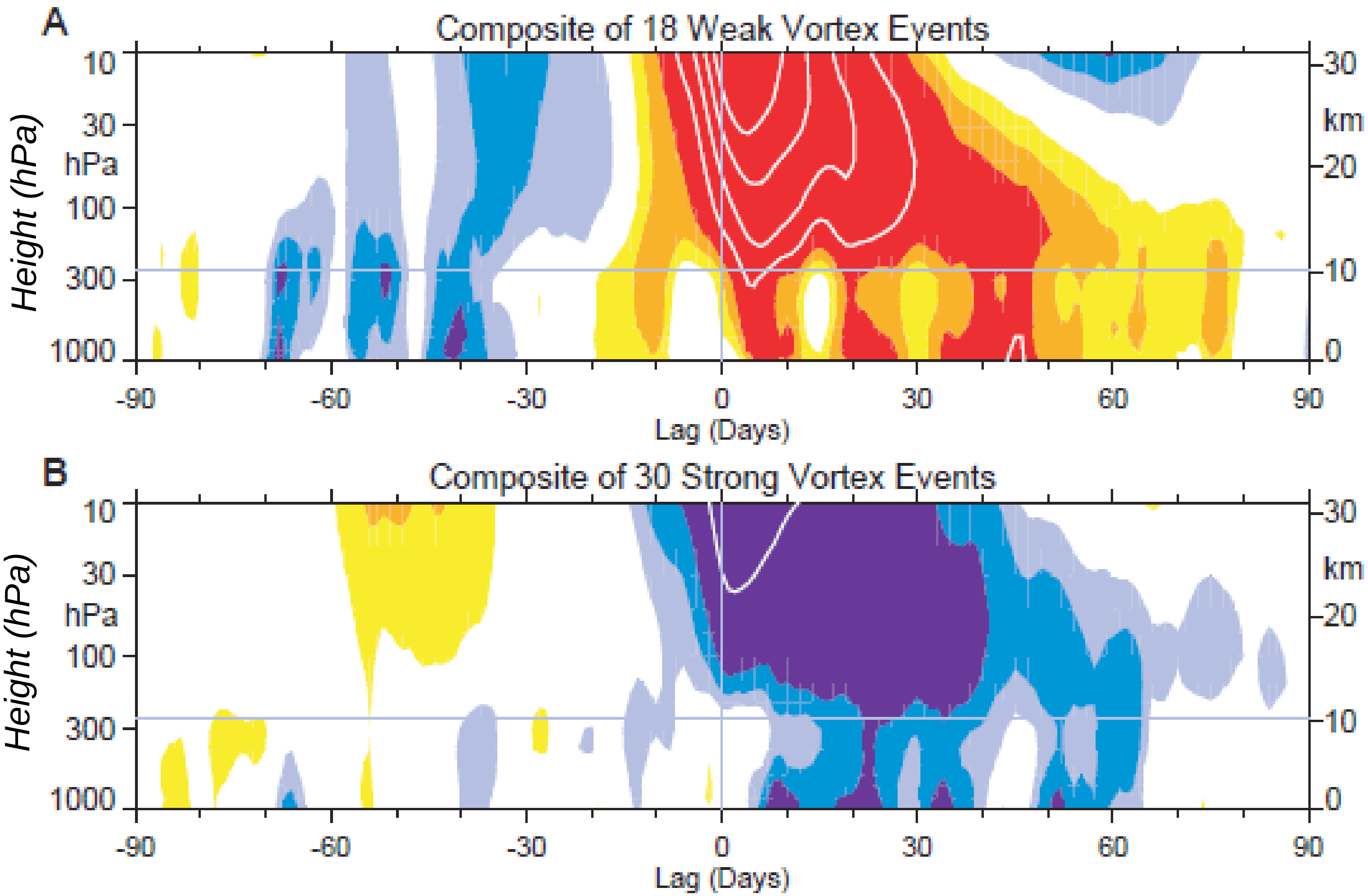


Leading structures of the monthly mean *50 hPa* height anomaly field for November (*SH*, left) and Jan-Mar (*NH*, right).

NAM: *Northern Annular Mode (AO, NAO)* → *Negative phase* of the *NAM* is related to *weak polar vortex* regimes.

[Thompson and Wallace, 1999]

Stratospheric variability: strato-tropo coupling



Days

Composites of time-height development of NAM (dimensionless).

Red: polar vortex *warm* and *weak*.

Downward propagation of the stratospheric anomalies.

Blue: polar vortex *cold* and *strong*.

Events determined by the dates on which the *10 hPa* annular mode values cross *-3.0* and *+1.5*.

These values are highly correlated (*0.95*) to with ***u*** at *10 hPa*, *60N*

positive values (+*1.5*)== *strong* vortex
negative values (-*3.0*)== *weak* vortex

[Baldwin and Dunkerton 2001]

Stratospheric variability: strato-tropo coupling

Stratospheric anomalous event January 2014

→

Record of cold temperatures

Chicago on January 7, 2014

https://www.climate.gov/news-features/event-tracker/wobbly-polar-vortex-triggers-extreme-cold-air-outbreak

LETTERS
PUBLISHED ONLINE: 13 JANUARY 2013 | DOI: 10.1038/NGEO1698
nature geoscience

Enhanced seasonal forecast skill following stratospheric sudden warmings *[Sigmond et al., 2013]*

M. Sigmond[1]*, J. F. Scinocca[2], V. V. Kharin[2] and T. G. Shepherd[1,3]

RMetS
Royal Meteorological Society

The predictability of the extratropical stratosphere on monthly time-scales and its impact on the skill of tropospheric forecasts

Om P. Tripathi,[a]* Mark Baldwin,[b] Andrew Charlton-Perez,[a] Martin Charron,[c] Stephen D. Eckermann,[d] Edwin Gerber,[e] R. Giles Harrison,[a] David R. Jackson,[f] Baek-Min Kim,[g] Yuhji Kuroda,[h] Andrea Lang,[i] Sana Mahmood,[f] Ryo Mizuta,[h] Greg Roff,[j] Michael Sigmond[k] and Seok-Woo Son[l]

Extreme stratospheric events improve wintertime tropospheric predictability.

[Tripathi et al., 2015]

METHODOLOGY

-CCM structure

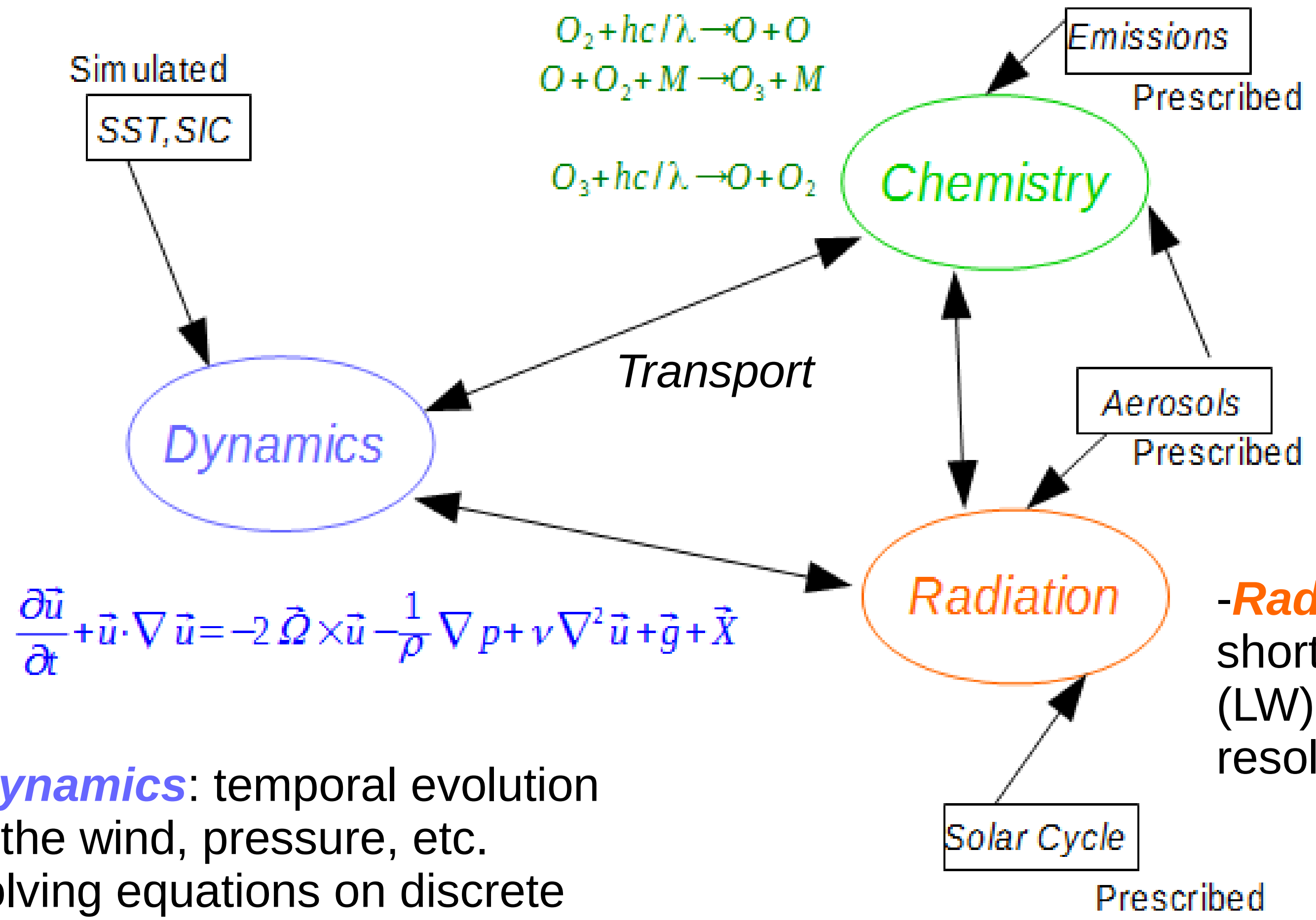
-SSW events detection

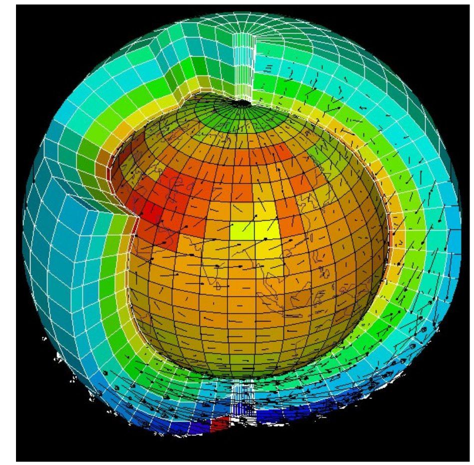
-NAM regimes characterization

Chemistry-Climate Model structure

ccmi
chemistry-climate model initiative

-***Chemistry***: solving equation governing (among all) stratospheric ozone. Several schemes of inorganic chemistry included



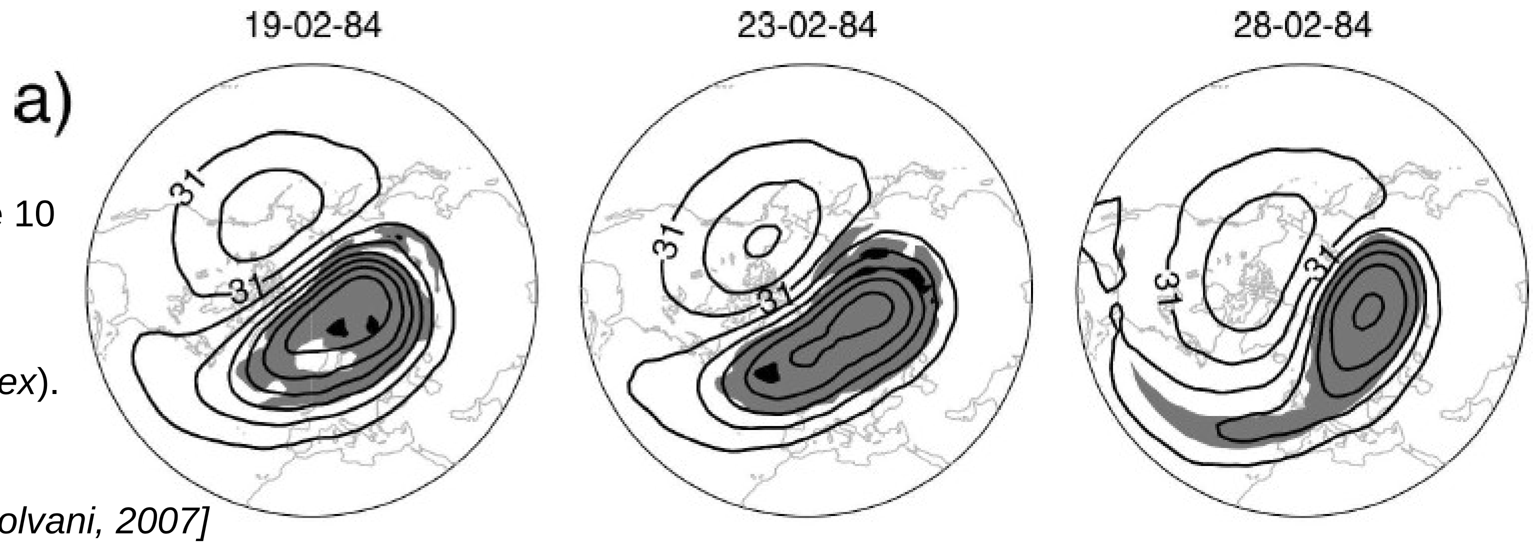


-***Radiation***: Separation of shortwave (SW) and longwave (LW) spectrum. Increased resolution (SW) for ozone.

-***Dynamics***: temporal evolution of the wind, pressure, etc.
Solving equations on discrete spatial and temporal grid.
Sub-grid processes are parametrized.

Identification of stratospheric anomalies: SSW

- ***<u>Date of occurrence</u>*** index (discrete): based on the definition used by *[Charlton and Polvani, 2007].*
- A SSW occurs when the zonal mean zonal wind at *60°N* and *10 hPa* becomes easterly, and the temperature gradient between 6*0°N* and 9*0°N* becomes positive during winter (November-March)(NDJFM).
- The *central date*: first day on which those conditions are met.
- *Final warming* (zonal wind easterly, but not returning westerly for 10 days before 30 April) and *minor warming* (only temperature gradient condition) are not included in this analysis.
- Shortest duration: 4 days. Minimum distance between events: 20 days



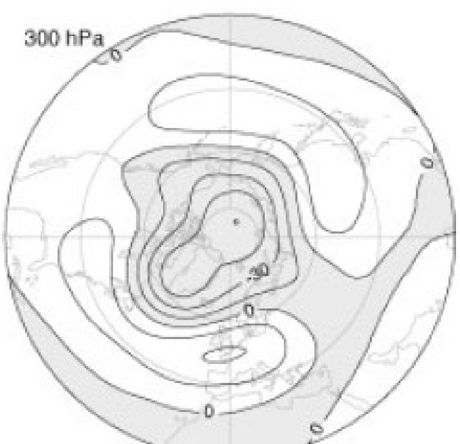
Geopotential height on the 10 hPa pressure surface. Shading shows potential vorticity greater than a threshold value (*polar vortex*).

[Charlton and Polvani, 2007]

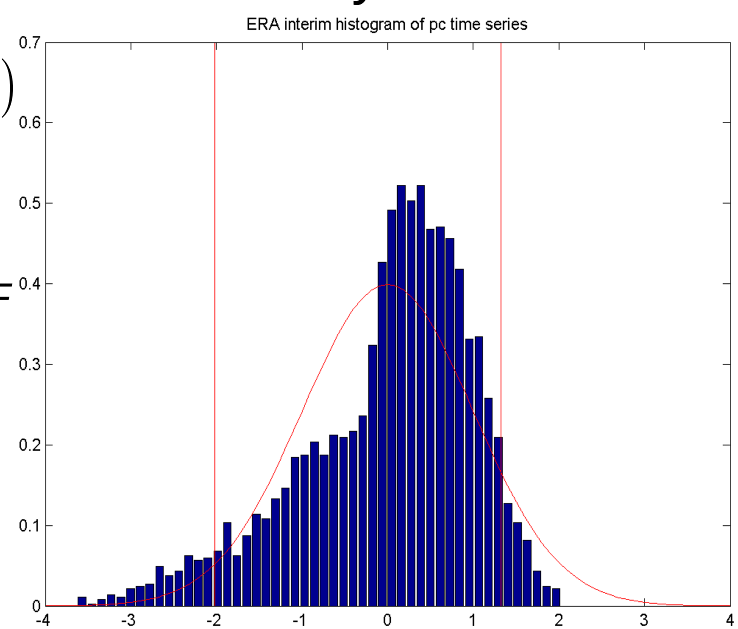
Identification of stratospheric anomalies: NAM regimes

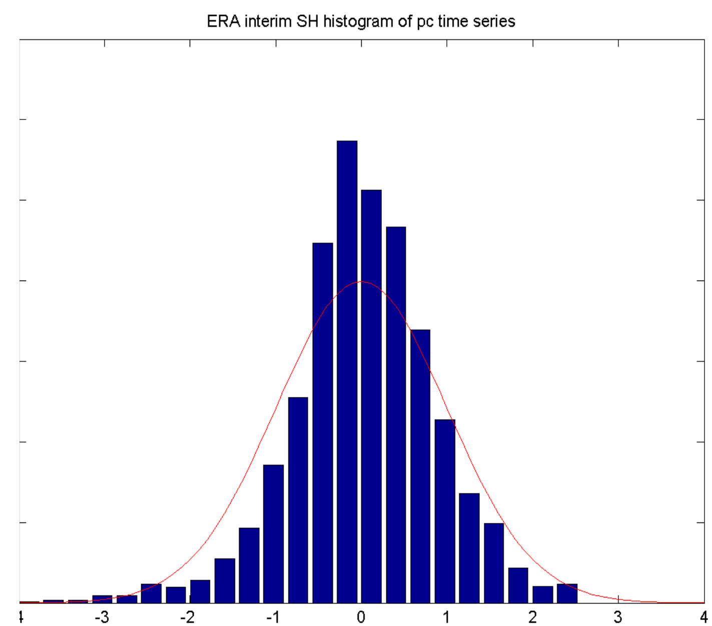
- ***NAM index*** (continue): based on the methodology reported by *[Baldwin and Thompson, 2009]*.
- NAM is defined as the leading *Empirical Orthogonal Function* (EOF) of the NH (*20°-90°N*) winter *zonal mean* geopotential height anomalies at *10 hPa*.
- The index is the standardized *Principal Component* (PC) of the leading EOF (*k=1*).
- Events of "*strong"* (95% prct) and "*weak"* (5% prct) vortex.
- Minimum duration of the event: three days. Minimum distance between two events: 30 days.

$$X'(t,\boldsymbol{S}) = \sum_{k=1}^{M} c_k(t)\,\boldsymbol{u_k}(\boldsymbol{S})$$



[Baldwin and Thompson, 2009]





CCMs and reanalysis

<u>*Considered models*</u>:
- -***CCSRNIES*** *[Akiyoshi et al. (2009)]*
- -***CMAM*** *[Scinocca et al. (2008)]*
- -***HadGEM3*** *[Walters et al. (2011)]*
- -***MRI*** *[Shibata and Deushi (2008)]*
- -***NIWA*** *[Morgenstern et al. (2013)]*
- -***SOCOL*** *[Stenke et al. (2012)]*

<u>***CMAM(1960-2000)***</u>

- Resolution: *3.75x3.75* lat,lon (≈*415x415* km)
- Uppermost level: ≈*100* km (*8.1*10-7 hPa*), 71 levels
- Used in operational seasonal forecast simulations from the *Canadian Centre for Climate Modelling and Analysis (CCCma)*.

<u>***NIWA(1960-1999)***</u>

- Resolution: *2.75x3.75* lat,lon (≈*272x415* km)
- Uppermost level: ≈*84* km (*0.1 hPa*), 31 levels

<u>***ERA-interim(1979-present)(ERA)***</u>

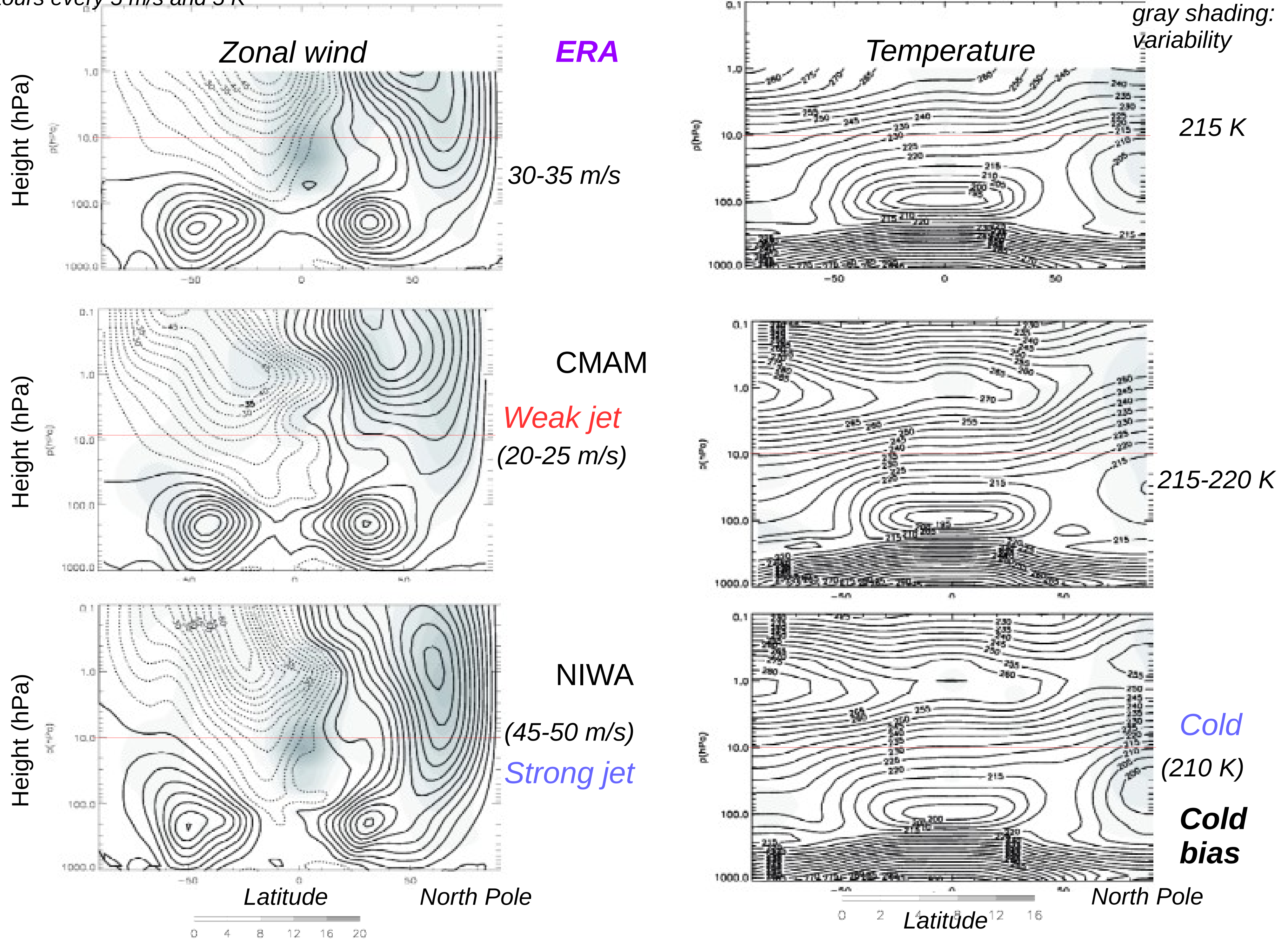
- Resolution: 1*x1* lat,lon (≈*110x110* km)
- Uppermost level: ≈*54* km (*1 hPa*), 37 levels
- Dataset created via data assimilation scheme (combining observations and forecast output from a weather model): at all times and spatial grid points.

[Dee et al., 2011]

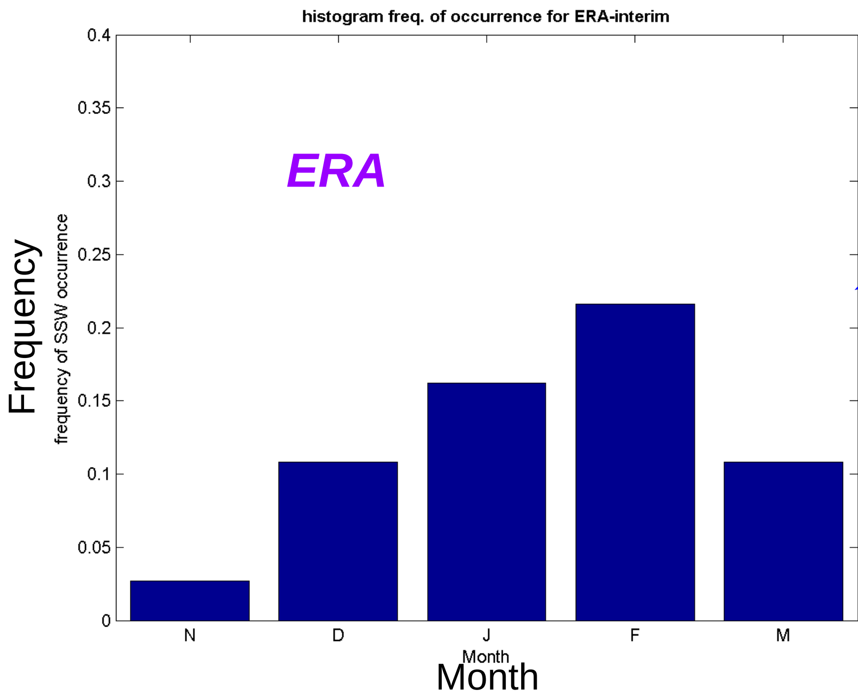
RESULTS

Atmospheric mean state(DJF) and interannual variability

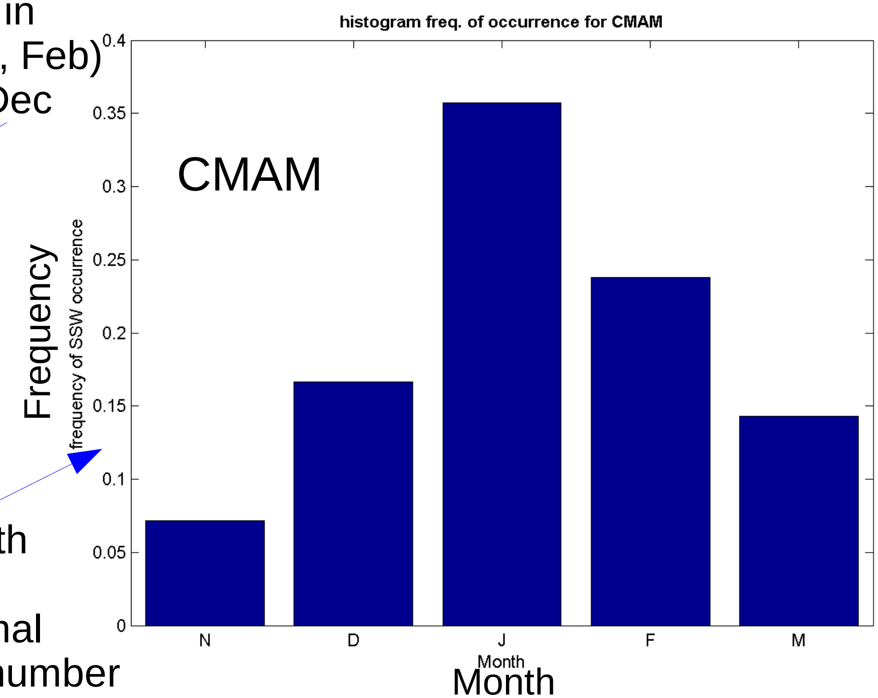
Contours every 5 m/s and 5 K



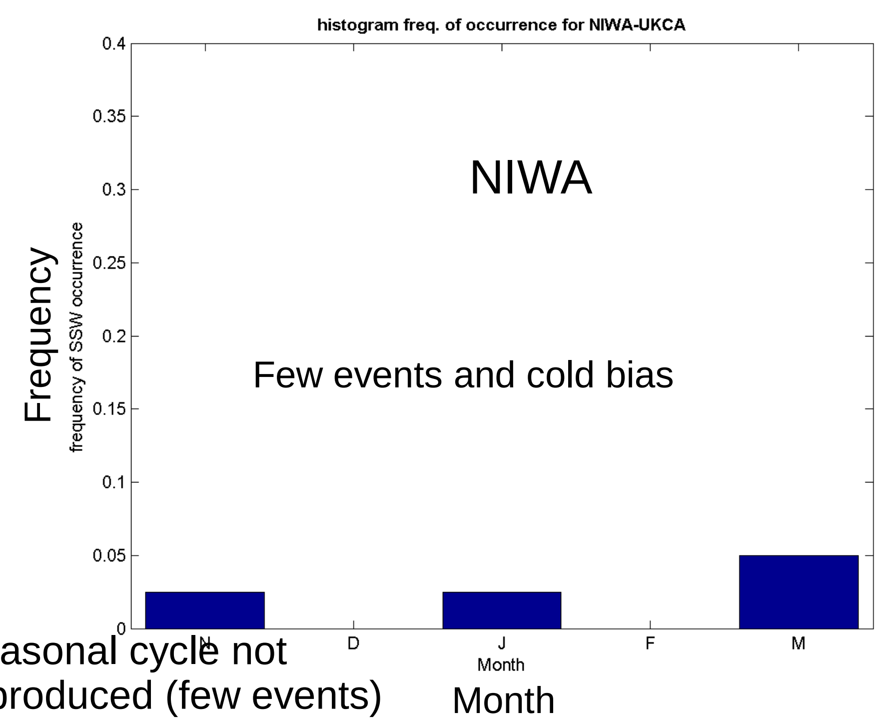
Intraseasonal SSW distribution



High frequency in mid-winter (Jan, Feb)
Few events in Dec and March

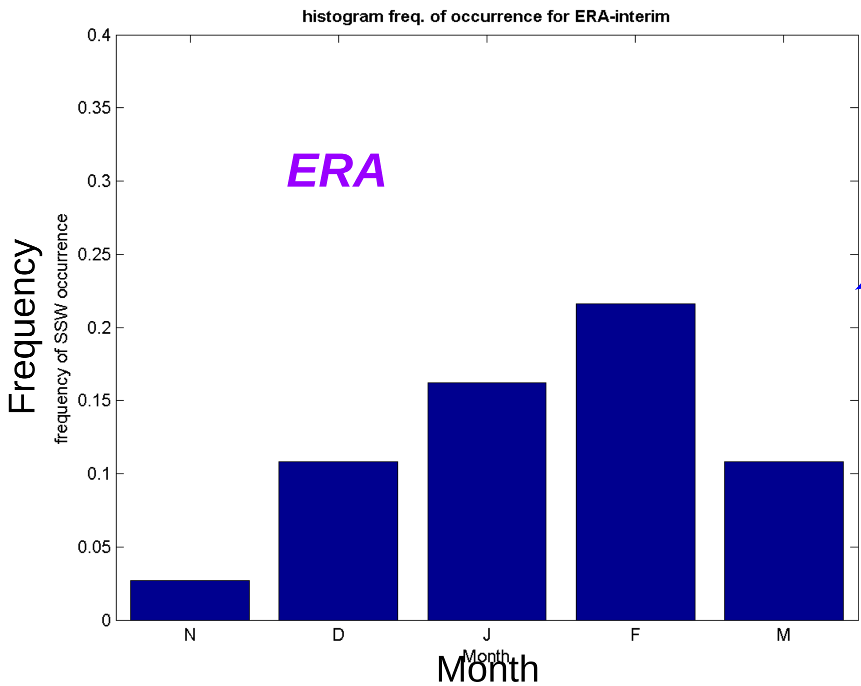


Accordance with reanalysis (correct seasonal cycle), higher number of events

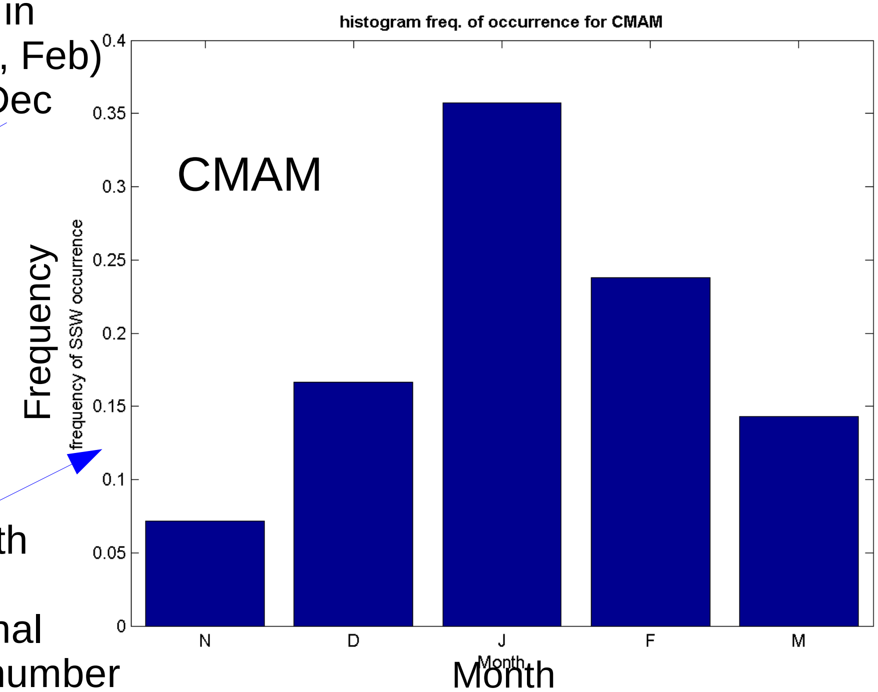


Seasonal cycle not reproduced (few events)

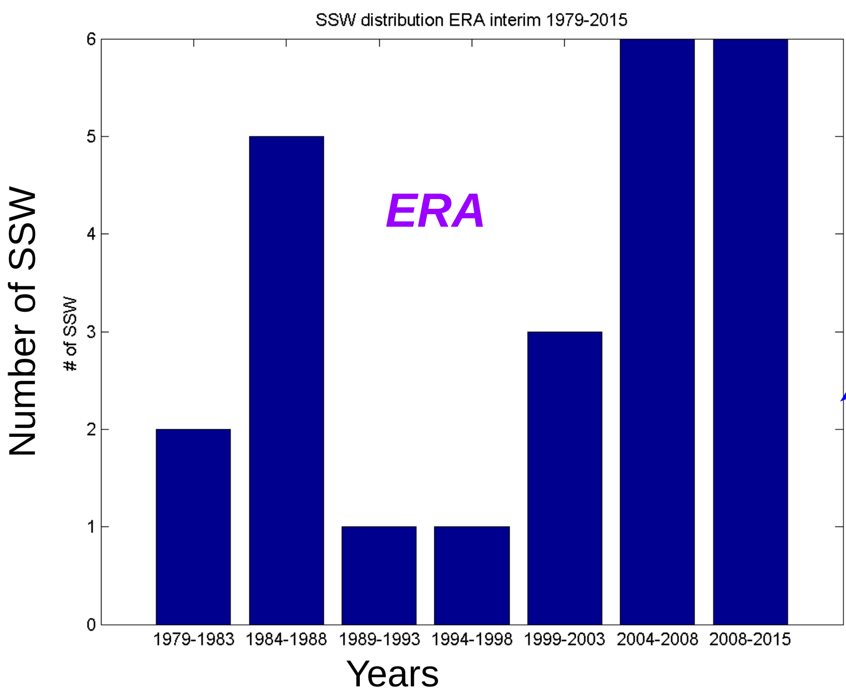
Interannual SSW distribution



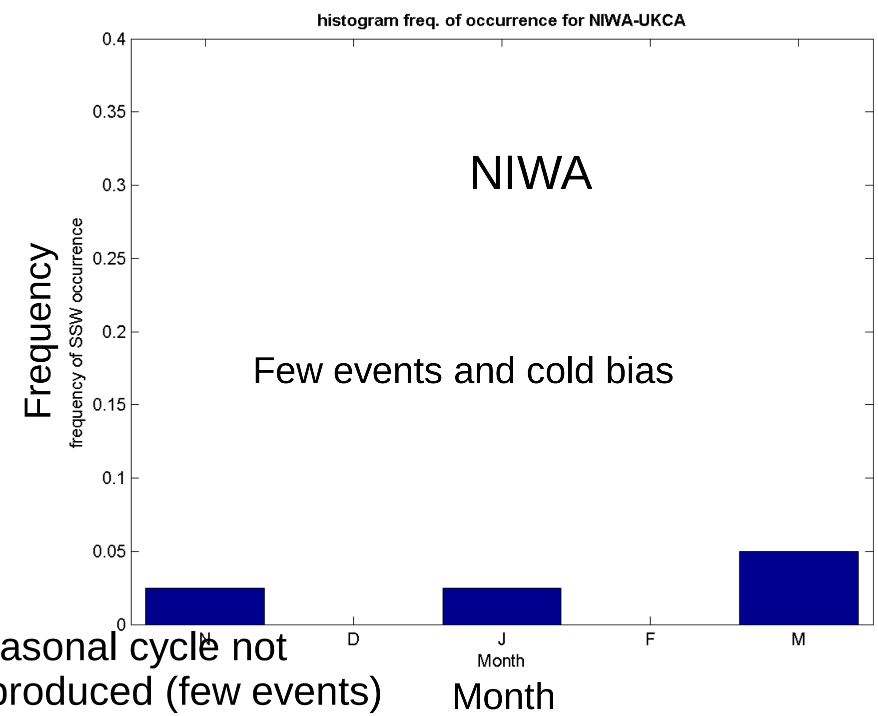
High frequency in mid-winter (Jan, Feb)
Few events in Dec and March



Accordance with reanalysis (correct seasonal cycle), higher number of events



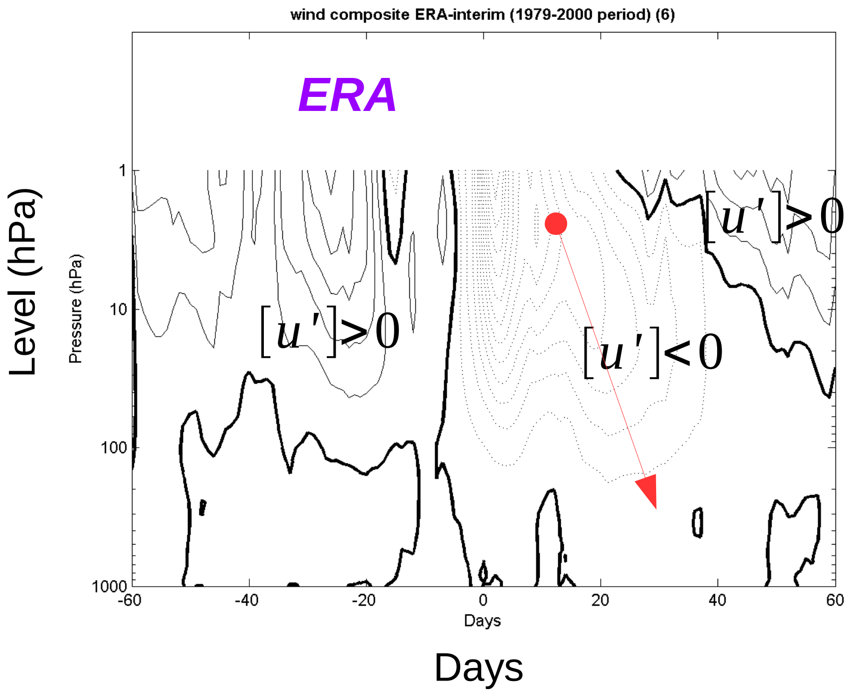
Multi-annual SSW distribution (low frequency variability)



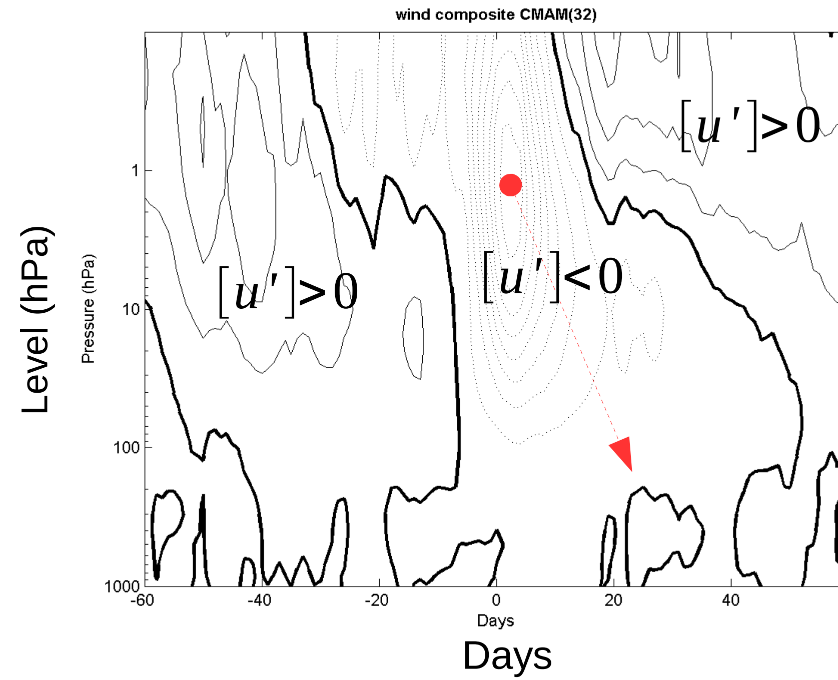
Seasonal cycle not reproduced (few events)

Downward propagation: SSW

Contours every 5 m/s

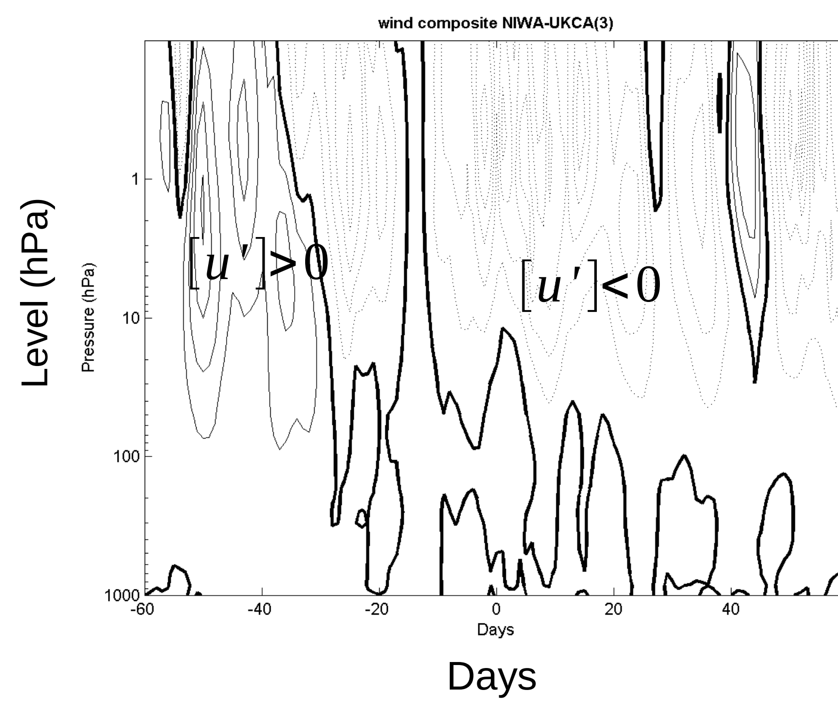


CMAM



[u'] is the zonal mean zonal wind anomaly (all anomalies calculated w.r.t. daily mean over all years)

NIWA

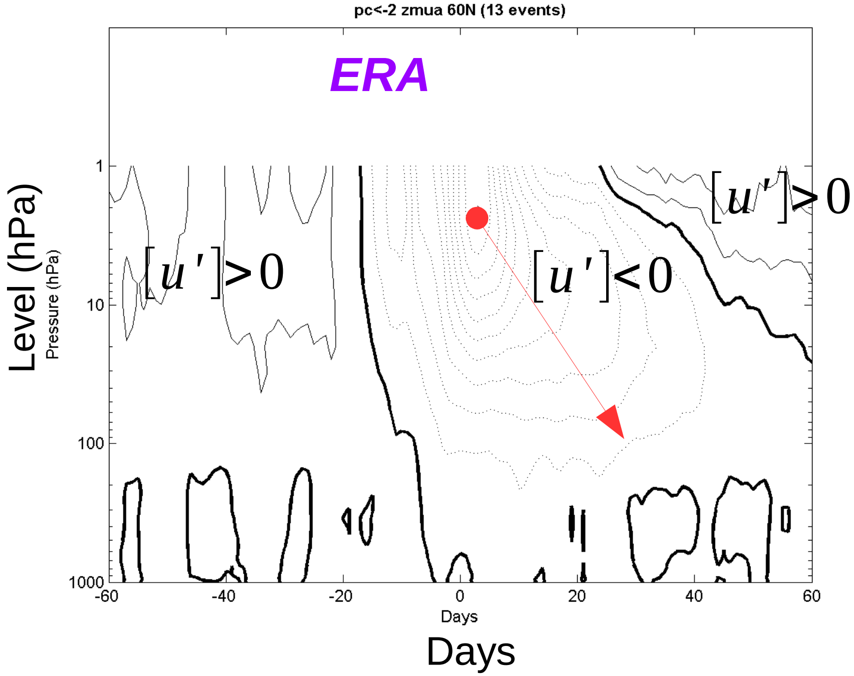


Delayed downward propagation of the negative zonal wind anomaly after SSW events.

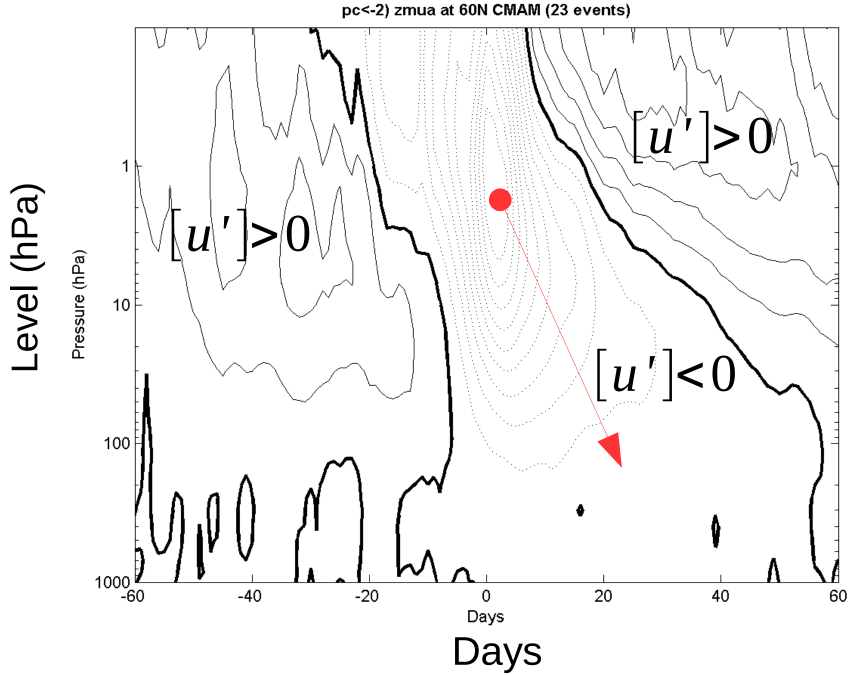
ERA : clear representation.
CMAM: present but not as strong as ERA.
NIWA: not realistic representation (few events).

Weak vortex NAM index

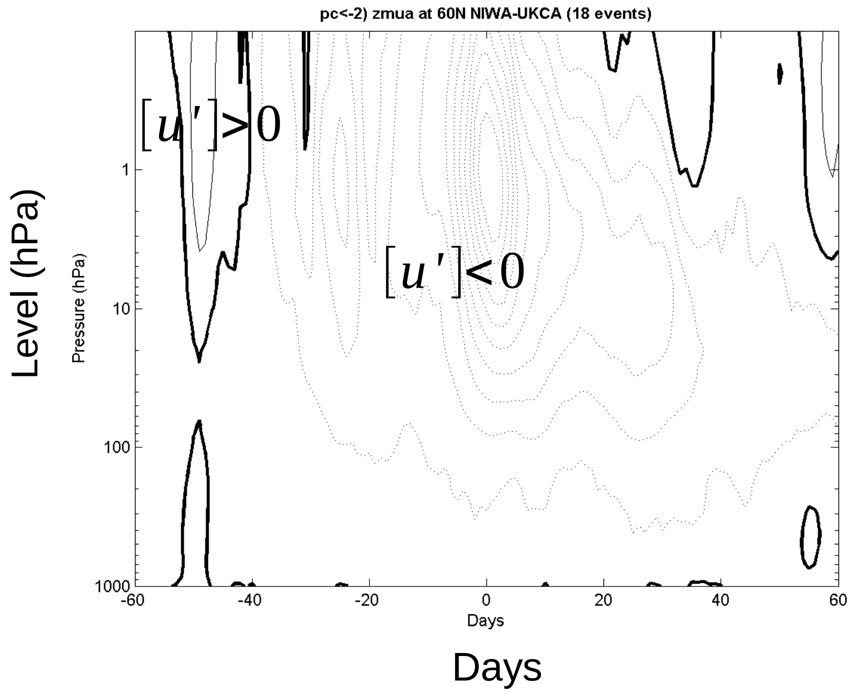
Contour every 5 m/s



CMAM



NIWA

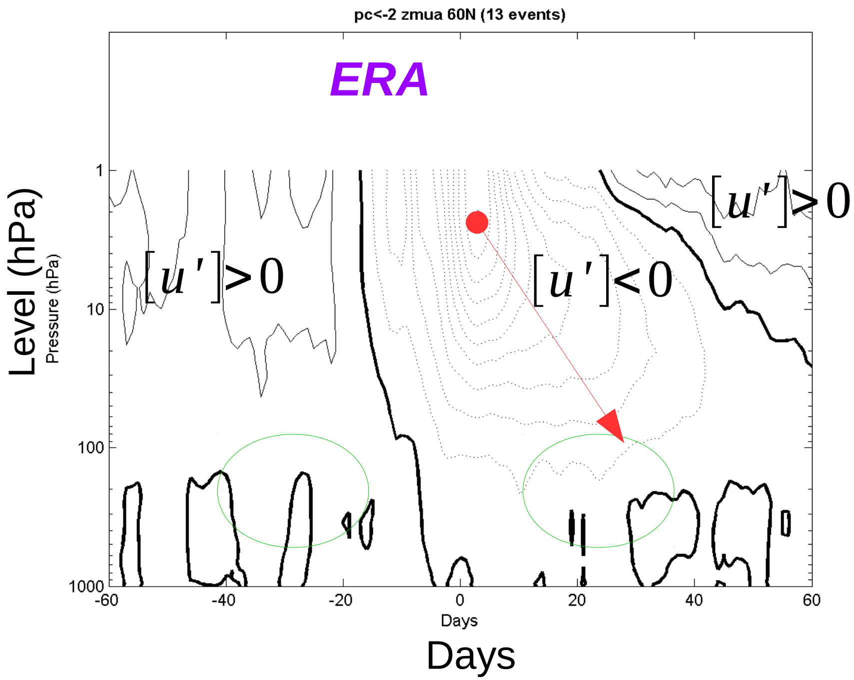


Delayed downward propagation of the negative zonal wind anomaly after NAM weak vortex events.

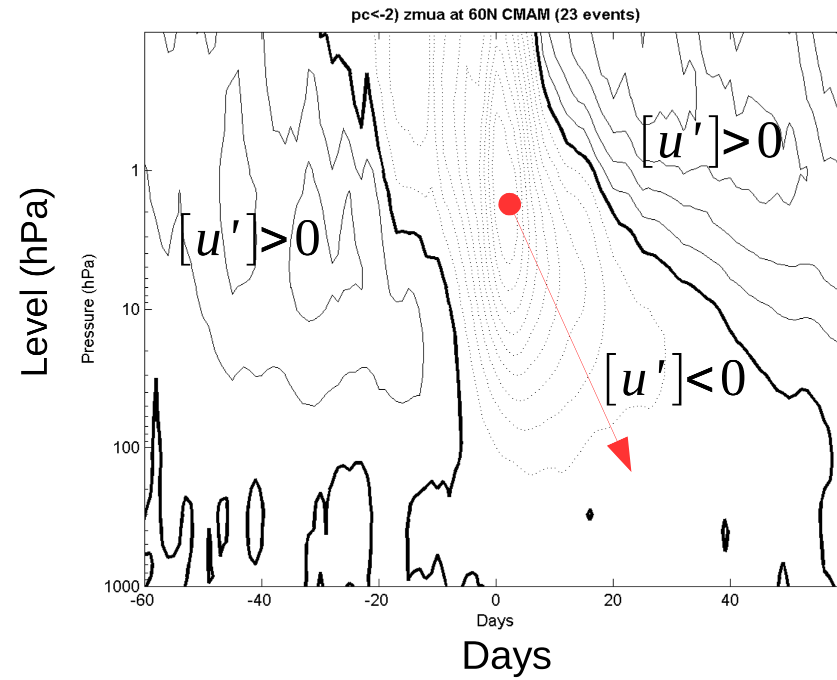
ERA: clear representation.
CMAM: quite similar to ERA.
NIWA: not realistic representation.

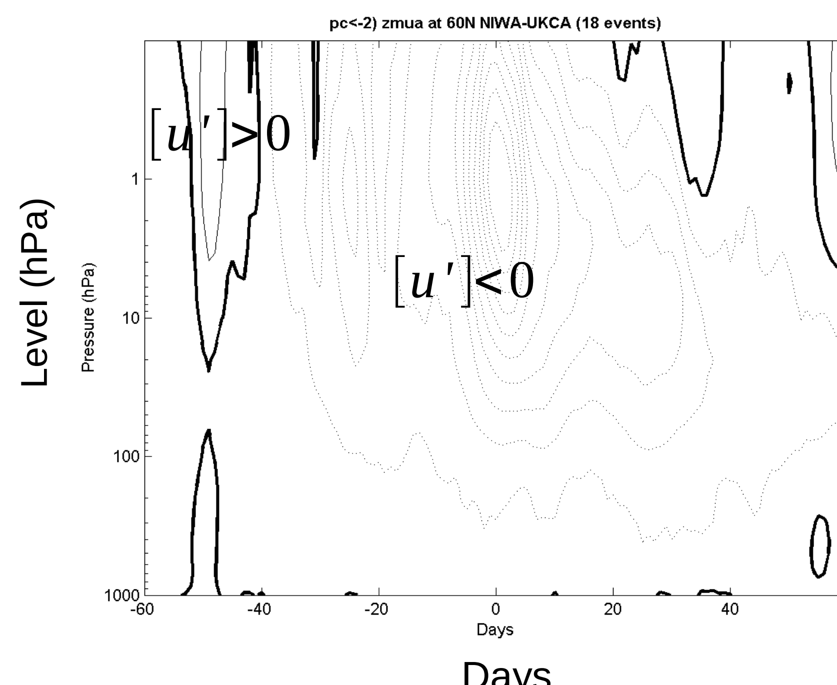
Weak vortex ***NAM index***

Contour every 5 m/s



CMAM





NIWA

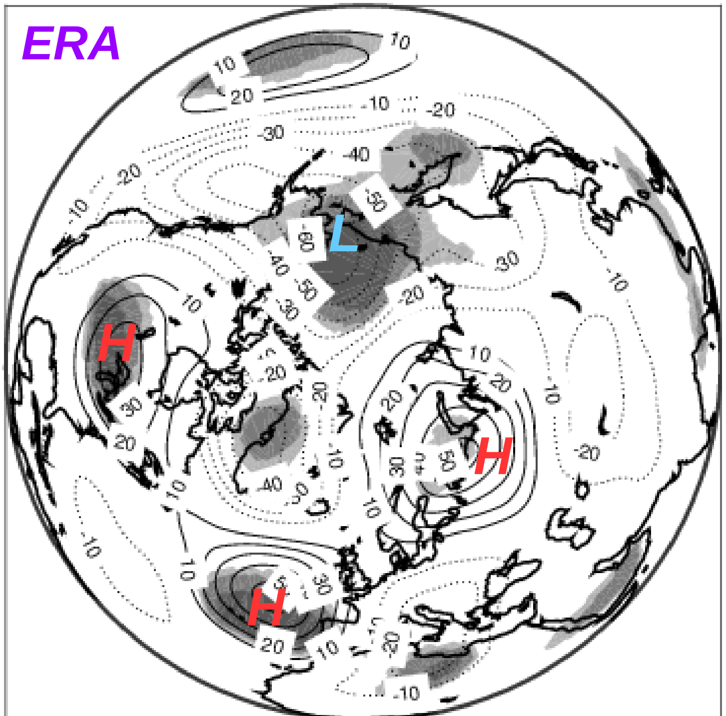
<u>Delayed downward propagation</u> of the negative zonal wind anomaly after NAM weak vortex events

ERA: clear representation.
CMAM: quite similar to ERA.
NIWA: not realistic representation.

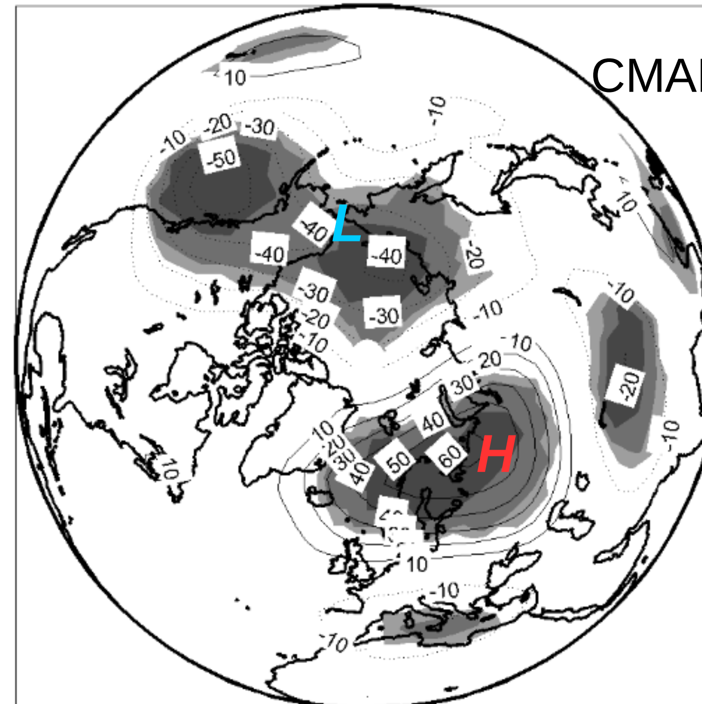
Weak vortex **30 days before**

Contours every 10 m

ERA-interim Z_{anom} 500 hPa (m) -30 dd pc<-2

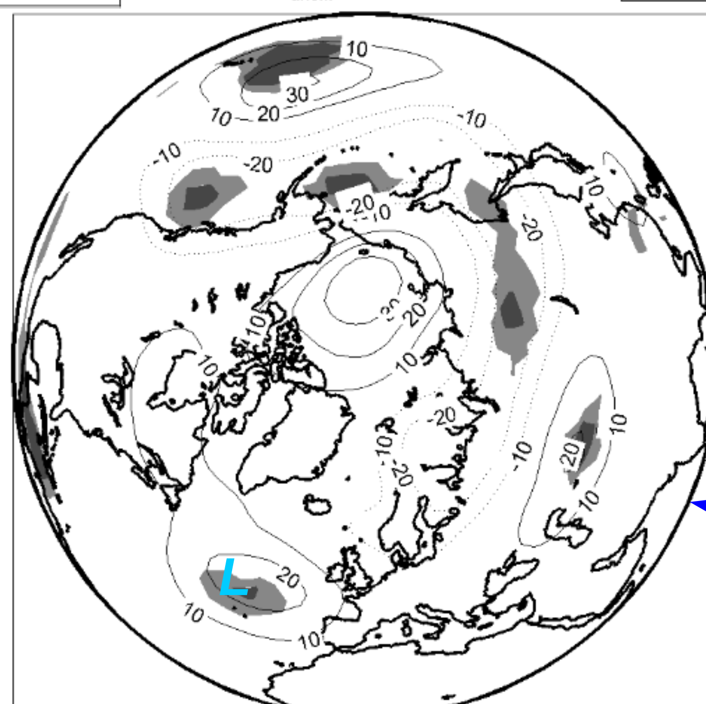


CMAM Z_{anom} (m) 500 hPa PC<-2 -30 dd



Composites of 500 hPa geopotential height anomalies (m)

NIWA-UKCA Z_{anom} (m) 500 hPa PC<-2 -30 dd



NIWA

Tropospheric pattern resembling Atlantic blocking event

SSW preconditioning (most SSW preceded by Atlantic blocking)

[Martius et al., 2009]

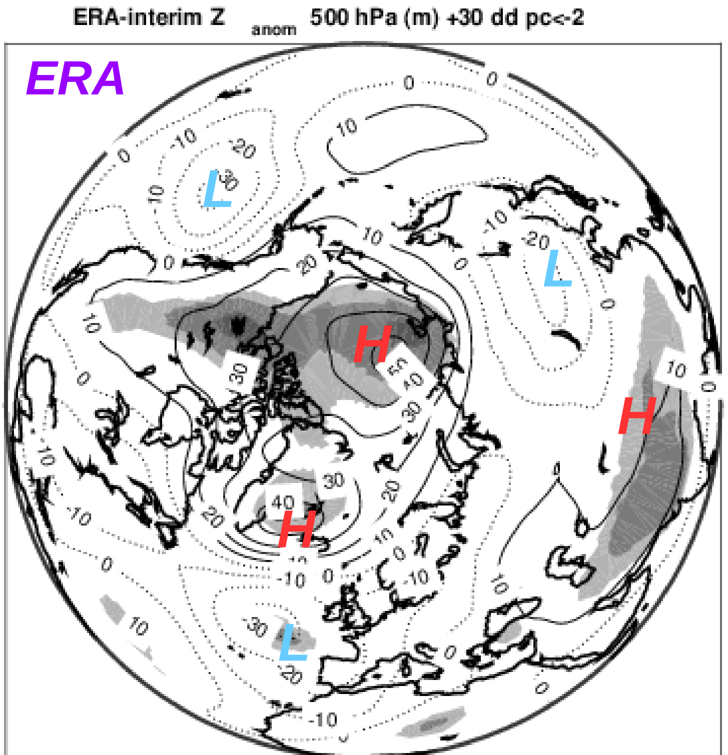
Dipole of positive-negative anomalies is visible

Shaded areas represent levels of confidence (99,95,90% levels)

No significant anomaly is visible

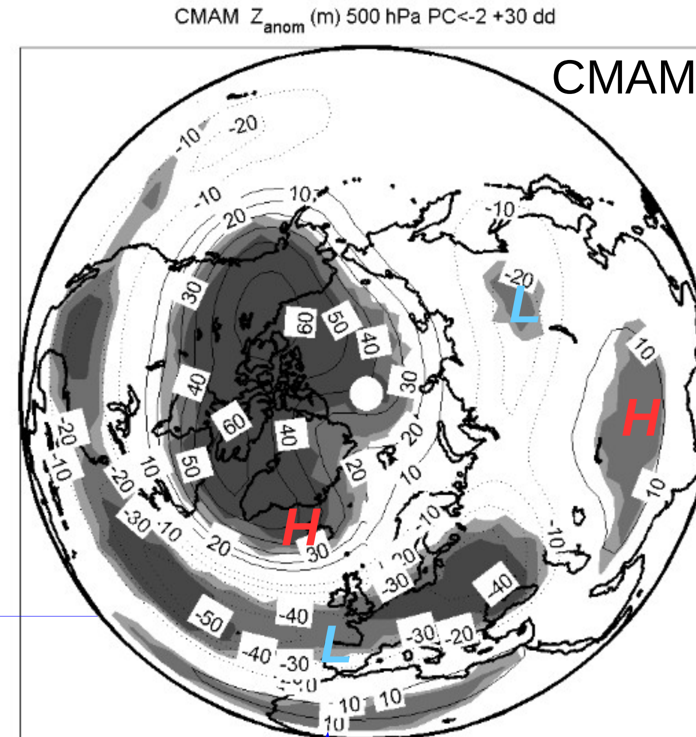
Weak vortex ***30 days after***

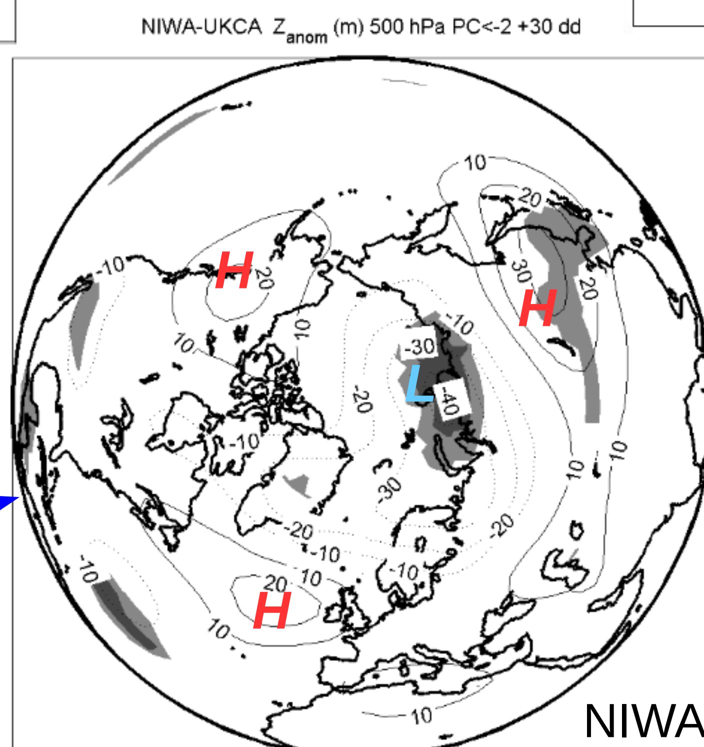
Contours every 10 m



Composites of 500 hPa geopotential height anomalies (m)

Atlantic sector of the NAM (NAO)





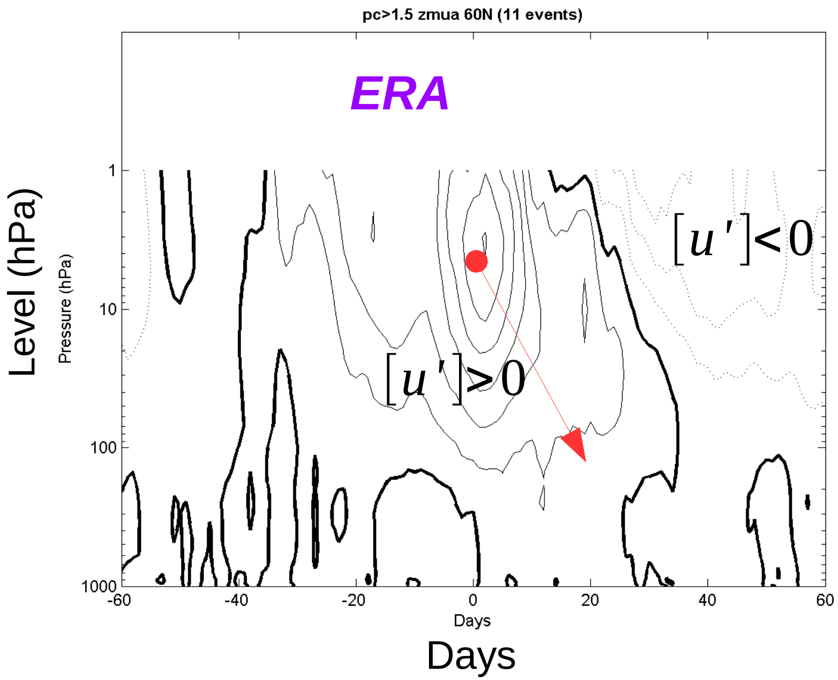
Anomalies affecting high and low latitudes (negative phase of the NAM represented)

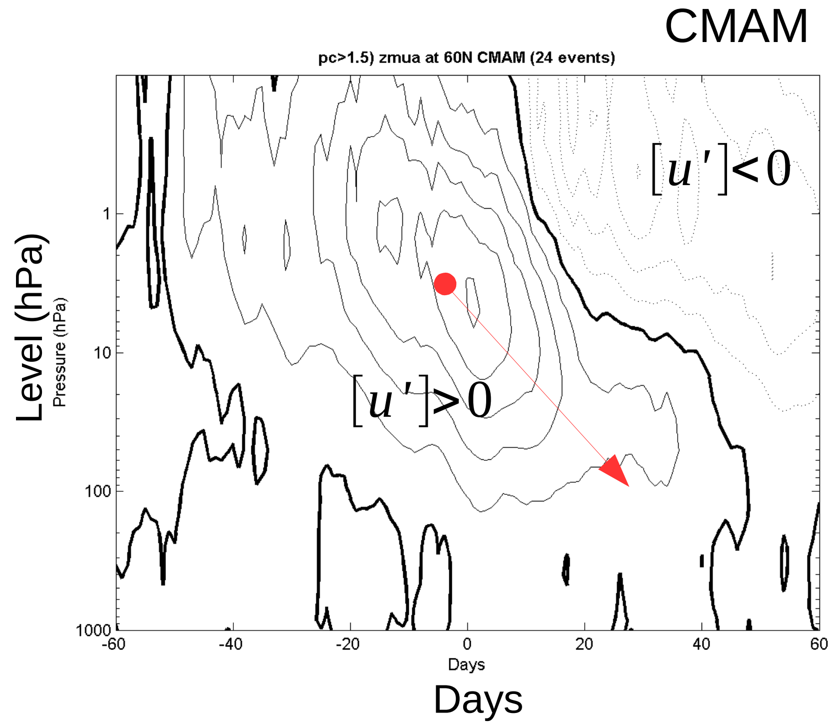
Few significant anomalies (negative phase of the NAM not represented)

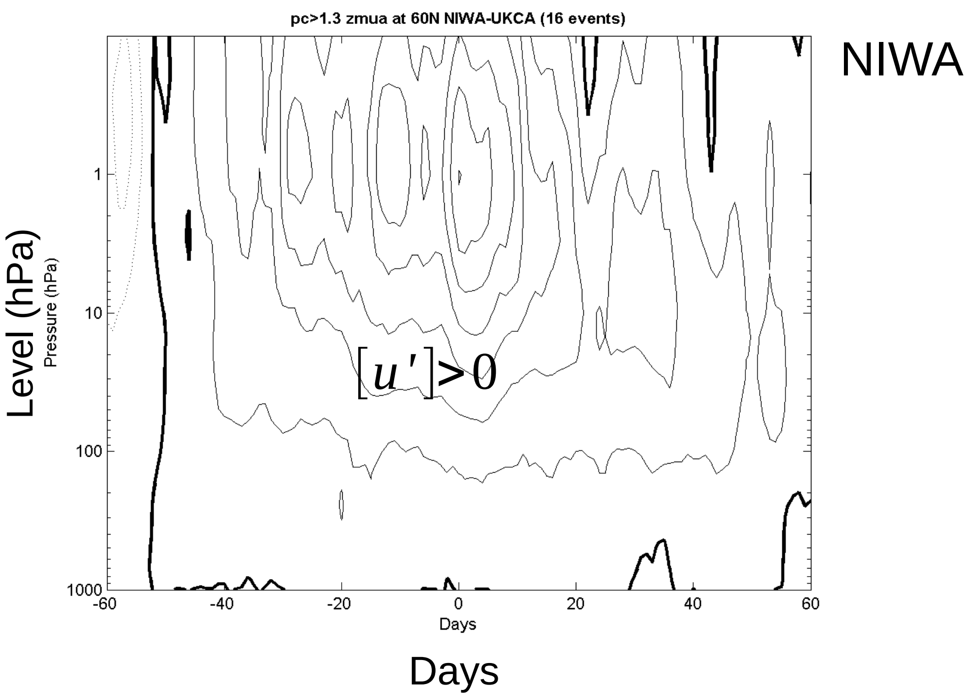
Anomalies affecting high and low latitudes. Different pattern from the reanalysis (negative phase of the NAM on the Atlantic sector well represented)

Strong vortex ***NAM index***

Contour every 5 m/s







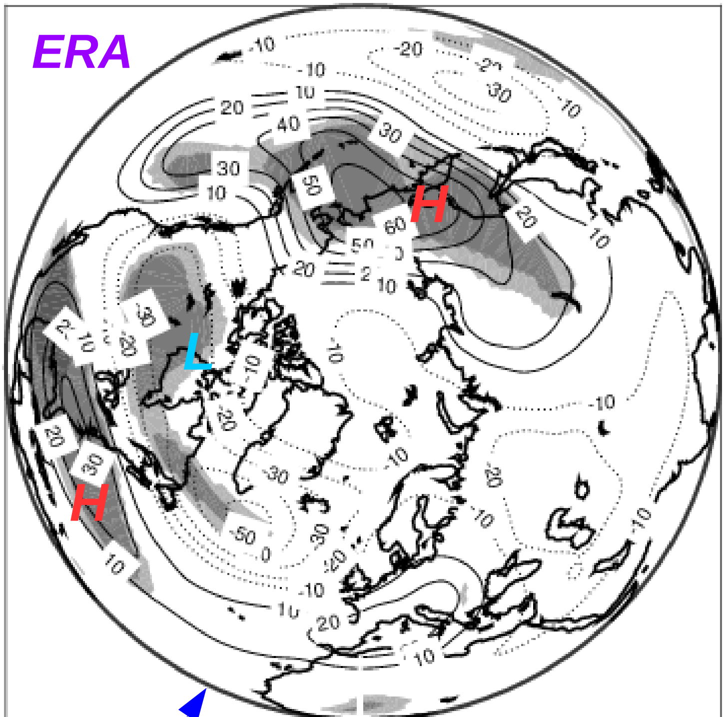
<u>*Delayed downward propagation*</u> of the positive zonal wind anomaly after NAM strong vortex events

ERA: clear representation.
CMAM: quite similar to ERA.
NIWA: not realistic representation.

Strong vortex 30 days before

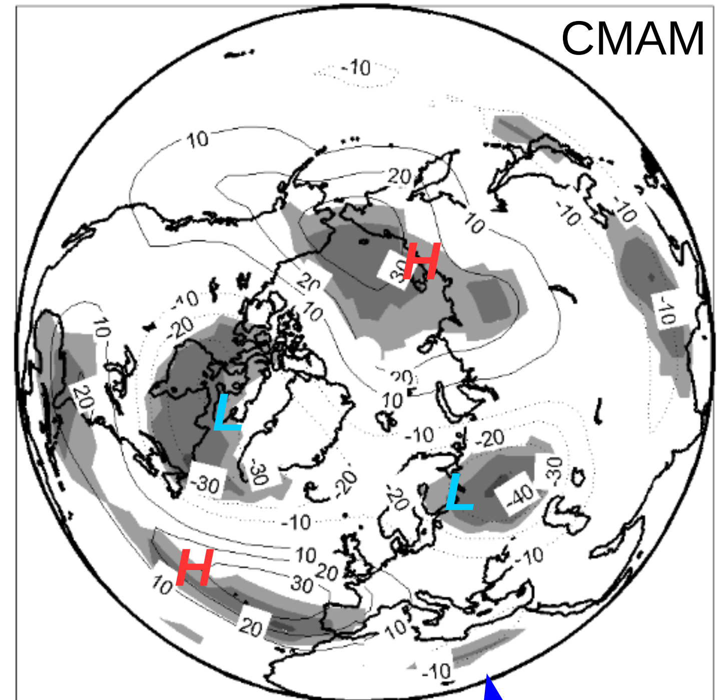
Contours every 10 m

ERA-interim Z_{anom} 500 hPa (m) -30 dd pc>1.5

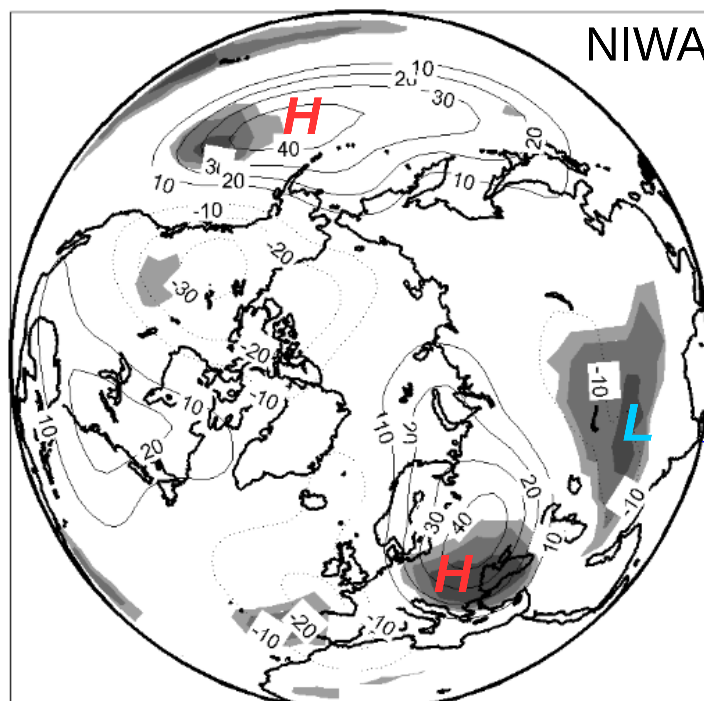


Composites of 500 hPa geopotential height anomalies (m)

CMAM Z_{anom} (m) 500 hPa PC>1.5 -30 dd



NIWA-UKCA Z_{anom} (m) 500 hPa PC>1.3 -30 dd



Tropospheric pattern: dipole at high latitudes and positive anomaly at mid-latitudes

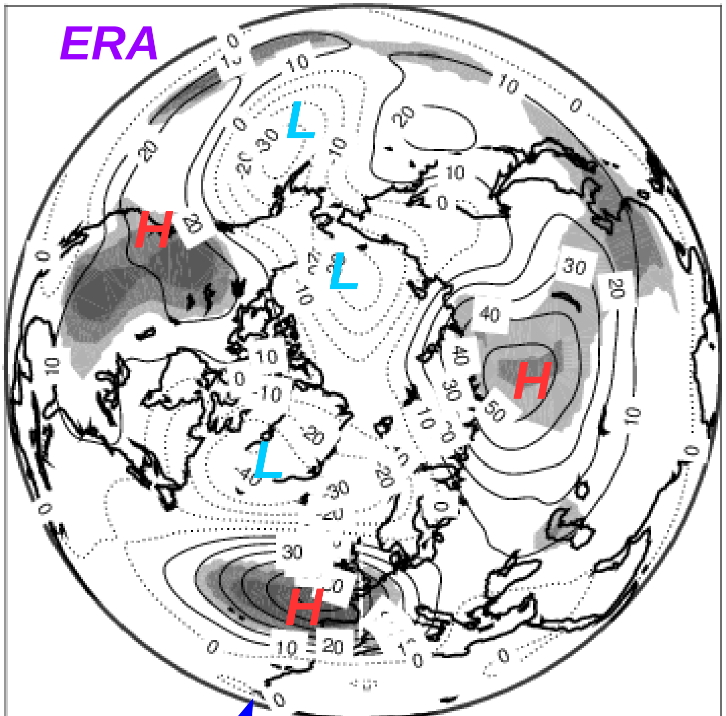
Pattern similar to the reanalysis at high latitudes

Different pattern from the reanalysis and smaller patterns of confidence (larger than weak vortex)

Strong vortex *30 days after*

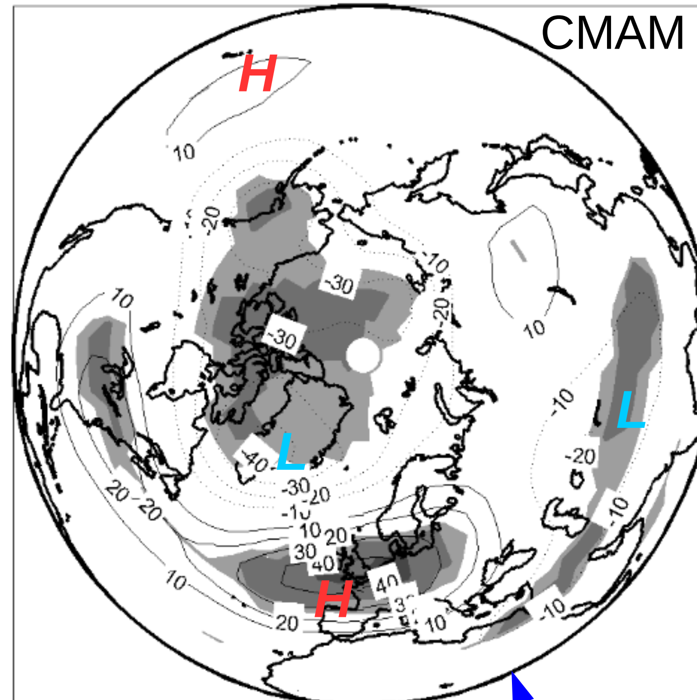
Contours every 10 m

ERA-interim Z anom 500 hPa (m) +30 dd pc>1.5

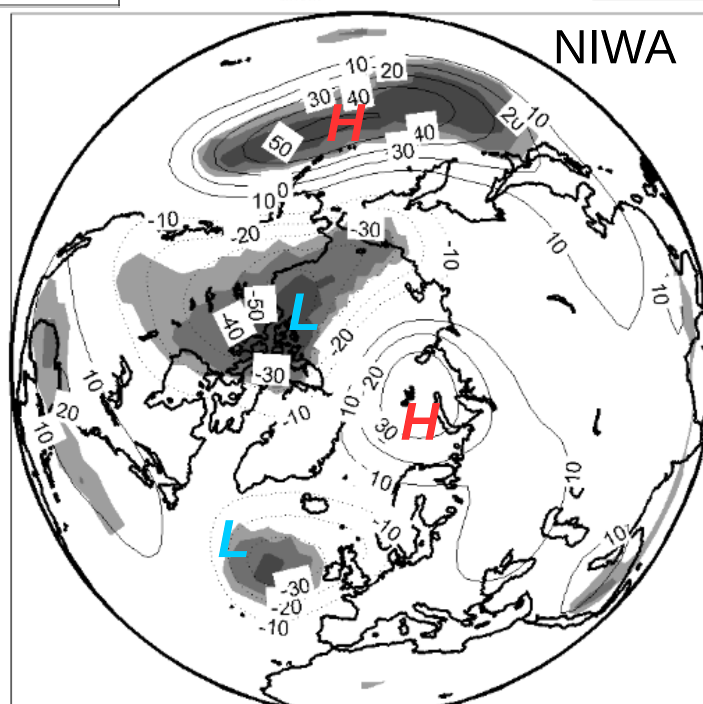


Composites of 500 hPa geopotential height anomalies (m)

CMAM Z anom (m) 500 hPa PC>1.5 +30 dd



NIWA-UKCA Z anom (m) 500 hPa PC>1.3 +30 d



Positive significant anomalies. Negative anomalies are smaller. Positive NAM phase is reproduced.

Positive phase of the NAM pattern is reproduced over the Atlantic sector but not in the Pacific nor in Asia

Different pattern from the reanalysis (positive NAM phase not represented).

Conclusions

- A comparison between CCMI models and reanalysis was made looking at the strat-tropo dynamical coupling using SSW and NAM indices.
- Possibility for *better predictions* of mid-latitude "weather" in weak and strong vortex regimes, requires models with a *good representation* of this *coupling*.
- *Stratospheric variability* (strong/weak polar vortex regimes in particular) is highly *related to the mean state*: reduced stratospheric variability is correlated with a colder polar stratosphere (e.g. NIWA).
- *Weak vortex regimes* seem to be preceded by tropospheric pattern resembling *blocking* event, in ERA but not in CMAM and NIWA.
- Models that do not show correct stratospheric variability, tend to have a uncorrect simulation of the NAM in the troposphere.

Perspectives:

- a)Extend analysis to all 14 models in *CCMI* dataset.
- b) Create a metrics to compare stratosphere-troposphere coupling between different models.

References

- *Thompson and Wallace, JGR, 1999*
- *Plumb, JMSJap, 2002*
- *Holton, 2004*
- *Baldwin and Dunkerton, Science, 2001*
- *Charlton and Polvani, AMS, 2007*
- *Baldwin and Thompson, QJRMeteorSoc, 2009*
- *Dee et al., QJRMeteorSoc, 2011*
- *Sigmond et al., Nature Geoscience, 2013*
- *Tripathi et al.,QJRMeteorSoc, 2015*
- *Martius et al., GRL, 2009*
- *Akiyoshi et al., JGR, 2013*
- *Scinocca et al., ACP, 2008*
- *Walters et al., GMD, 2011*
- *Shibata and Deushi, AnGeo, 2008*
- *Morgenstern et al.,JGR 2013*
- *Stenke et al., GMDD, 2012*

Backing slides

Models characteristics

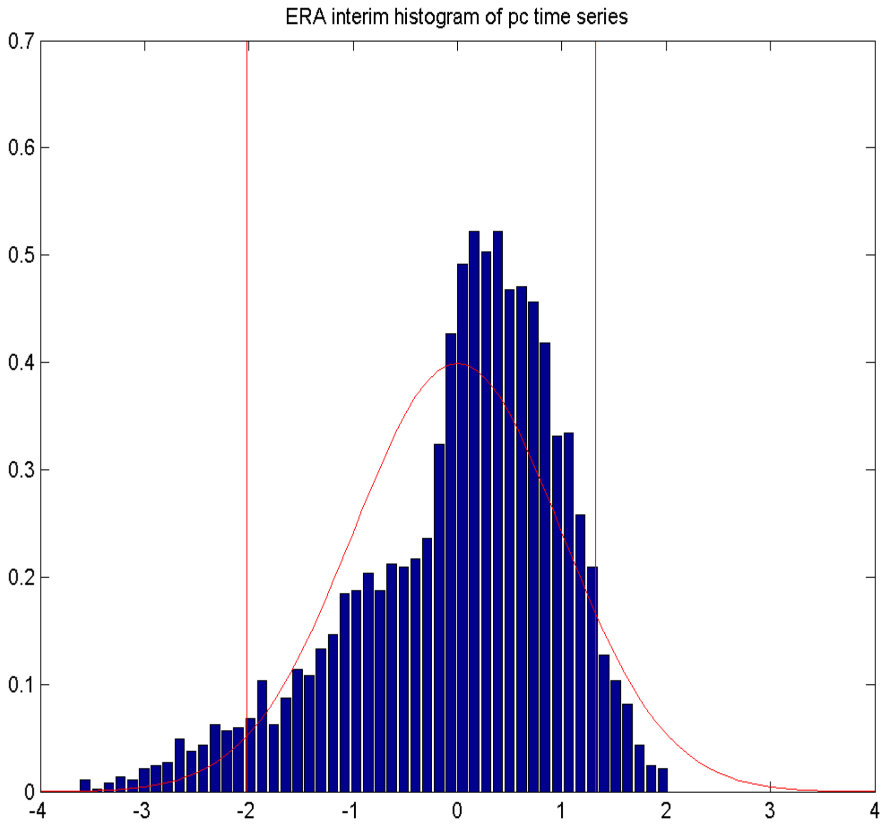
Model name	***Resolution***	***Uppermost Level***	***Chemistry***	***ODS/GHG Emission***	***Ocean***	***QBO***
CMAM	T47	0,00081 hPa	Strat-trop	N.A.	Fixed	Internal
CCSRNIES	T42/L34	0,012 hPa	Strat.	N.A.	N.A.	Nudged
HadGEM3	1,25/1,875 L85	84 km	Strat-trop	N.A.	Coupled	N.A.
MRI	T42	0,01 hPa	Strat-trop	N.A.	Coupled	Internal
NIWA	2,5/3,75 L60	84 km	Strat-trop	Mixing Ratio	Coupled	Internal
SOCOL	T42	0,01 hPa	Strat	N.A.	N.A.	Nudged

Detailed informations about the forcings can be found in:

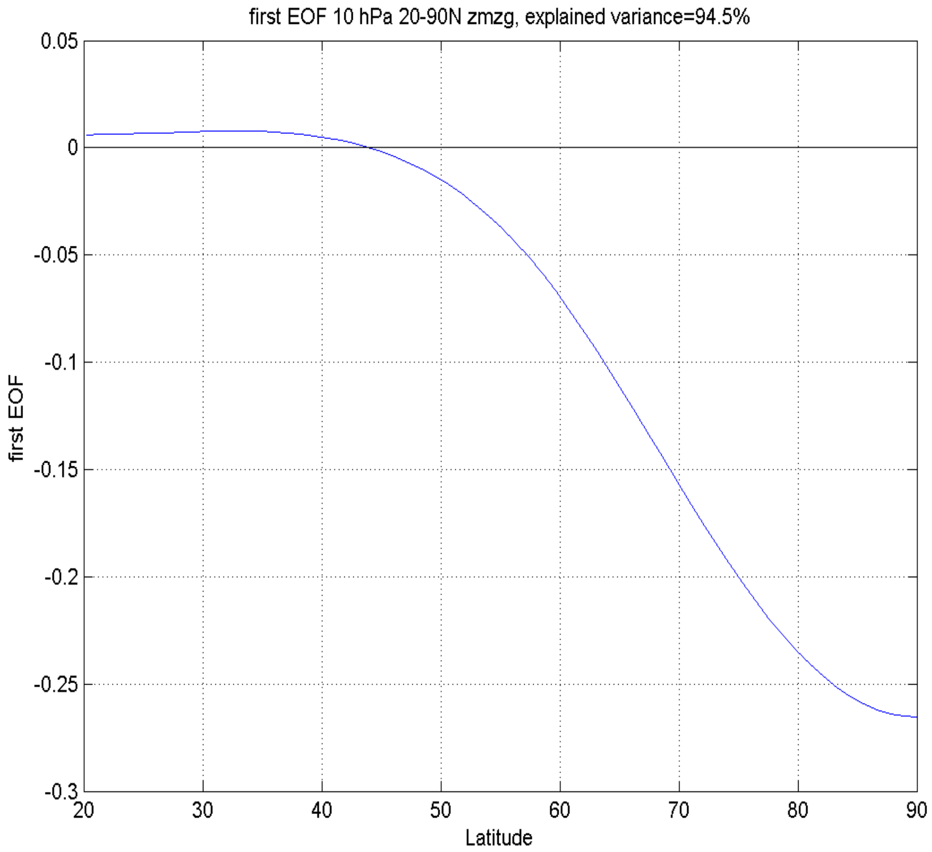
[Eyring et al., SPARC Newsletter, 2013]

Backing slides

ERA



Standardized PC



Leading EOF

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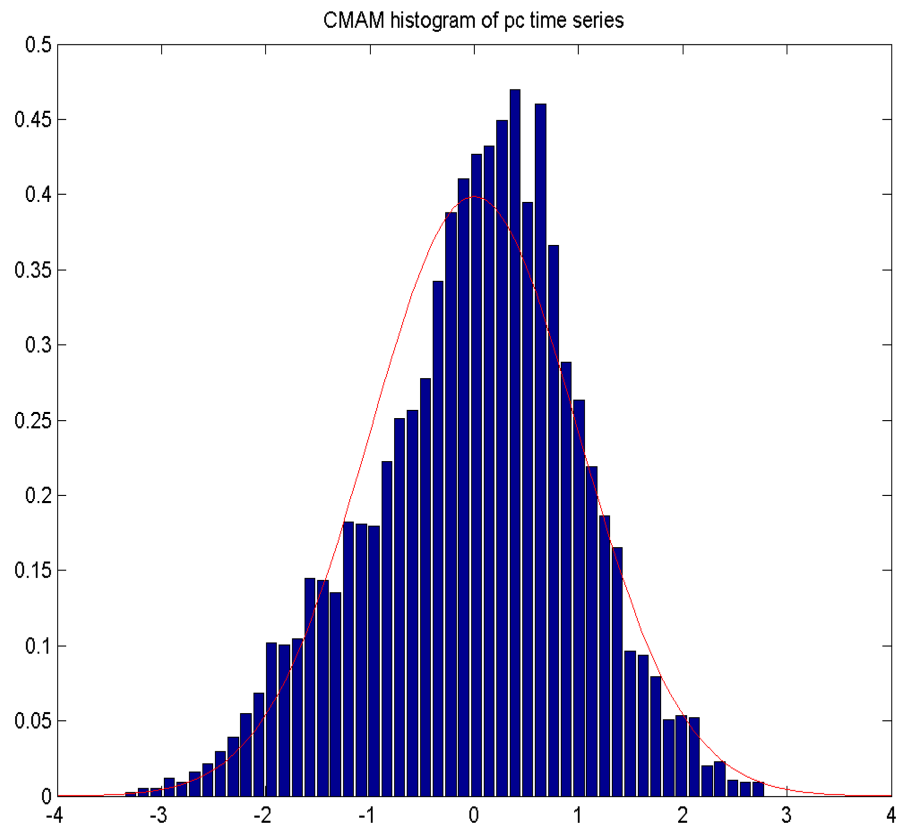
CMAM



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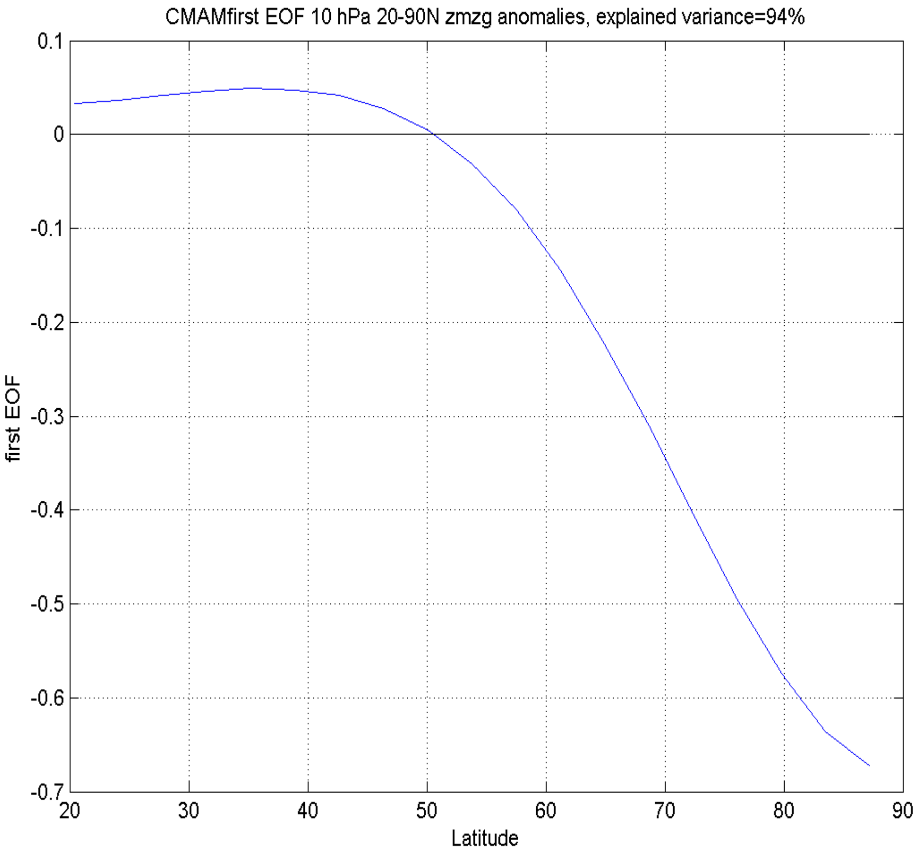

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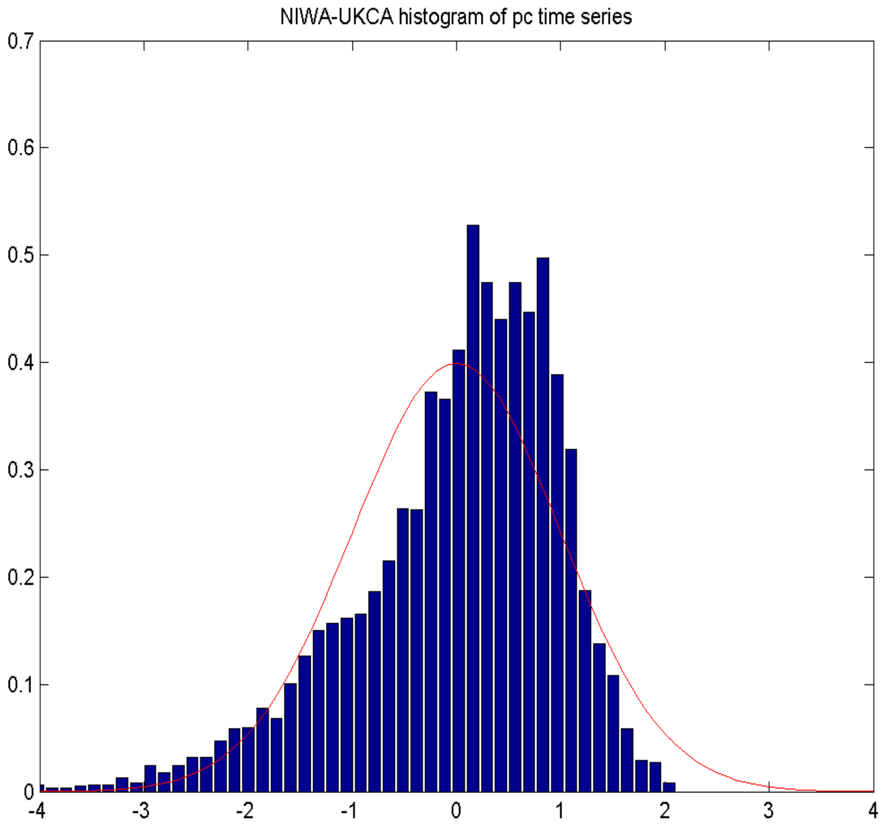
NIWA



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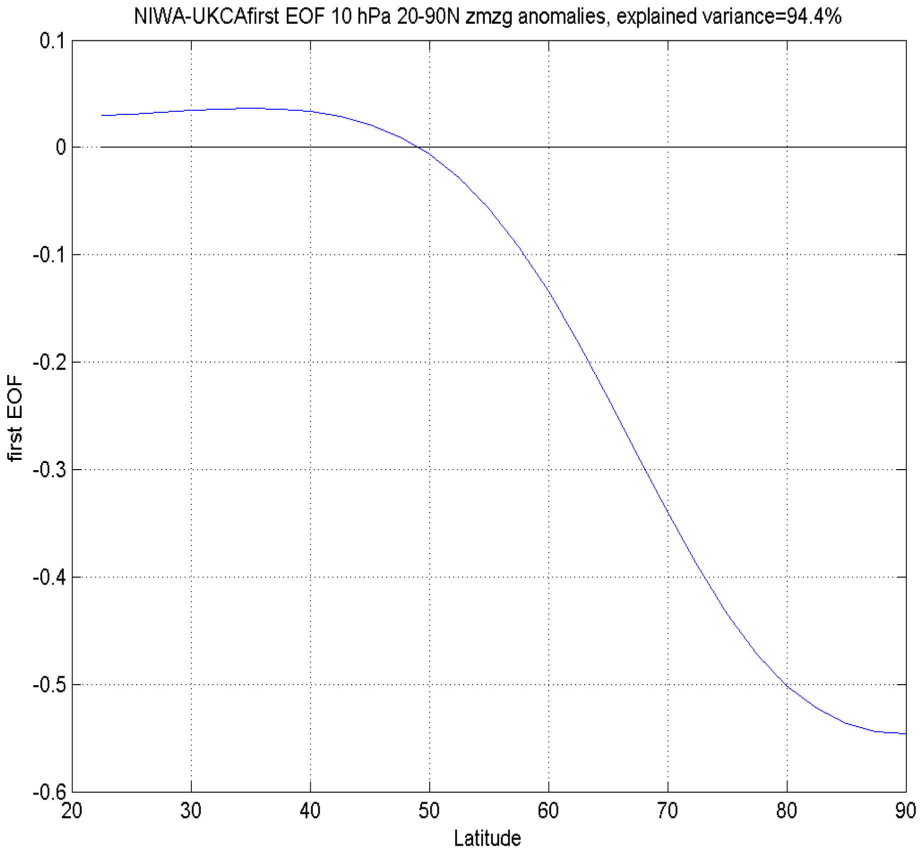

Leading EOF

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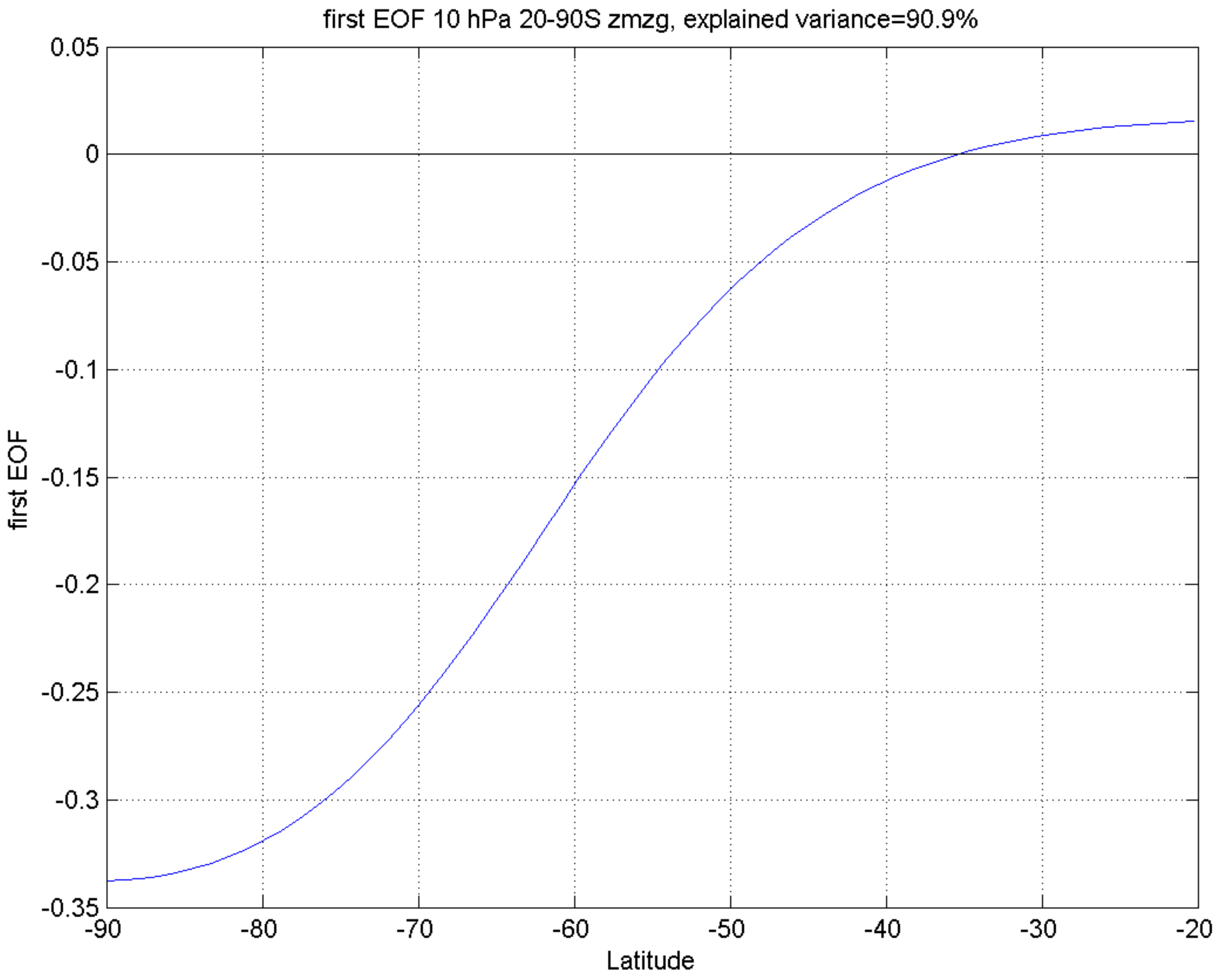
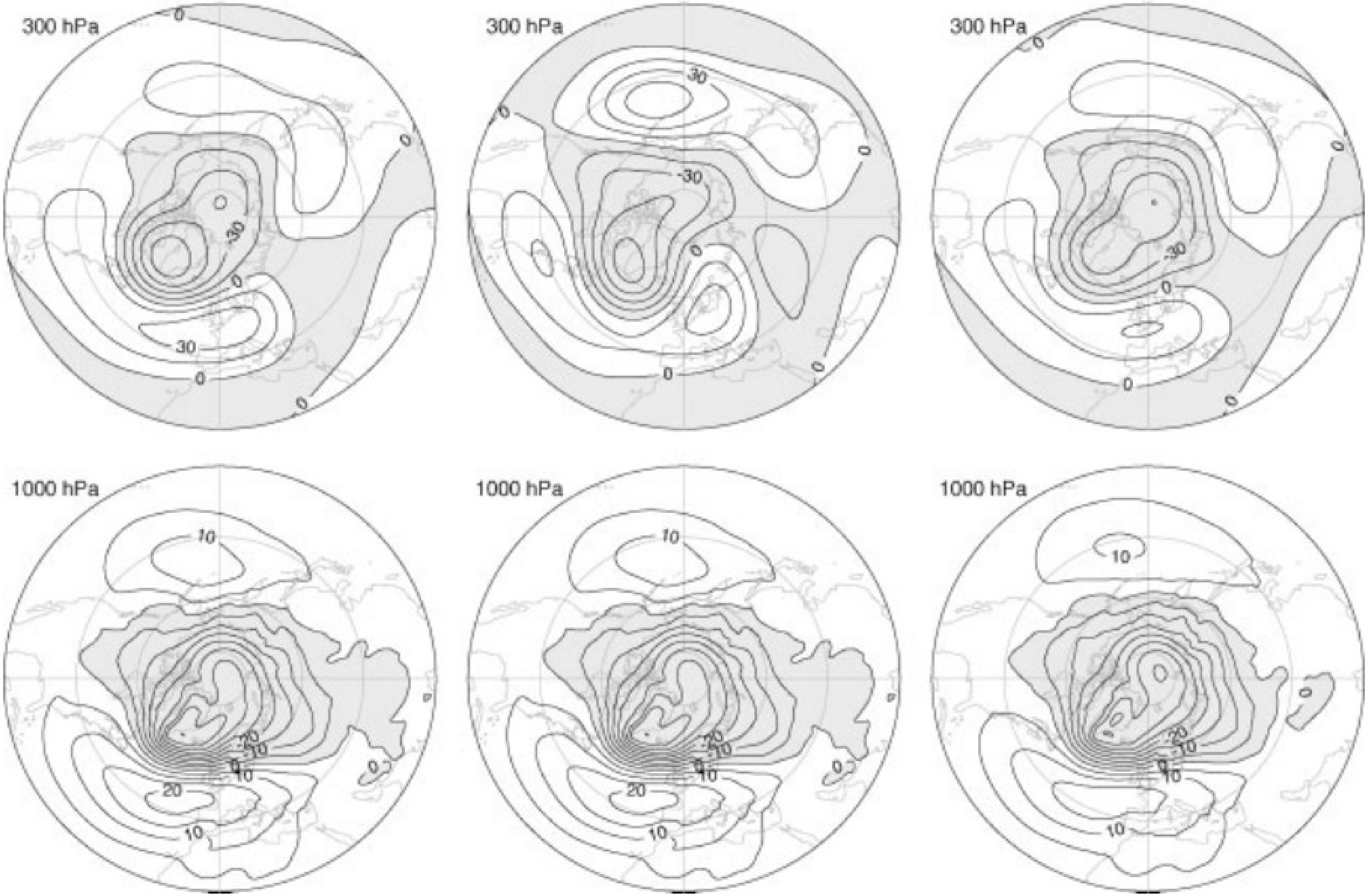


<u>First EOF SH for ERA-interim</u>

Differences indeces in [Baldwin and Thompson, 2009]

Backing slides

Surface-based NAM | *Height-dependent NAM* | *Zonal-mean NAM*



Surface-based NAM: Difficult reproduction of upper stratosphere annular modes.

Height-dependent NAM: Robust at stratosphere and surface, but not at upper troposphere.

Zonal-mean NAM: Less dependent on subjective choice, higher correlation between strat-trop variab, requires less data.